ENGINEERING MATERIALS MACHINE TOOLS AND PROCESSES

BY THE SAME AUTHOR

MECHANISM AND THE KINEMATICS OF MACHINES

In collaboration with K. NEWTON, B.Sc., M.I.Mech.E., M.I.A.E.

THE MOTOR VEHICLE

ENGINEERING MATERIALS MACHINE TOOLS AND PROCESSES

By

W. STEEDS

A.C.G.I., B.Sc. (Eng.) London,
A.M.I.Mech.E., M.I.A.E.

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PREFACE

To say that the present age is one of specialisation may be trite but is, nevertheless, very true and this specialisation, although undoubtedly necessary and indeed unavoidable, in view of the complexity of modern practice and the enormous range of modern knowledge, has sometimes serious consequences.

For the engineer it is particularly important that he should have a background of general knowledge of all the branches of his profession behind his specialised knowledge of one particular branch. This background the student should acquire, on the theoretical side, during his attendance at a technical school or engineering college, while on the practical side he should get it during his apprenticeship. Since engineering works have become steadily more and more specialised during the last half century, it has become increasingly difficult for the apprentice to get any experience of a really wide nature during his apprenticeship, and many engineers at the present time definitely lack a wide background of knowledge of their profession.

The necessity for such a background has been stated at various times by eminent engineers and was expressed in a recent paper to the Institution of Engineers and Shipbuilders in Scotland by E. D. Russell who said, speaking of apprenticeship courses: "This course . . . should aim at producing not merely a trained specialist craftsman, but should be devised in such a manner as to give the man a superficial knowledge of other trades, in order that he may appreciate the difficulties of these trades and may see his work as part of the finished whole and not just as a small individual operation."

This book has been written to help students, apprentices, and others, entering or engaged in the engineering industry, to acquire a knowledge of the elements of the basic branches of mechanical engineering other than design. It is realised, of course, that a really sound knowledge of any practical subject cannot be obtained merely by reading a text-book but requires first-hand experience of the work; nevertheless, a good deal of time can be saved and the assimilation of practical knowledge can be greatly facilitated if a good text-book is used. It is hoped that this book will be useful in this capacity.

The book, which is roughly divisible into two parts, starts with a chapter on the testing and inspection of engineering materials, because the student cannot properly appreciate the chapters that follow unless he has some knowledge of the tests whose results are quoted therein. Then come two chapters which are designed to give the reader a general knowledge of the ferrous and non-ferrous materials which are available to the engineer. The purely metallurgical side is only mentioned very

briefly because, though important, it is highly specialised and the engineer needs to know little more of its specialised aspects than will enable him to realise when the trained metallurgist should be called in. The production of castings, both in sand moulds and by die-casting, is then dealt with and this is followed by consideration of hand and machine forging operations and drop stamping. The next chapter deals with press-tool work and spinning, branches of engineering practice which most students, and many trained engineers, rarely come across but which are undoubtedly of great importance. A chapter on the general aspects of welding and a short chapter on plastic moulding round off the first half of the book.

The second half deals with machining processes and naturally starts with a consideration of lathe work. A chapter is devoted to the experimental work done on the relation of the life of cutting tools to the various factors involved, such as cutting angles, size of cut, cutting speed, etc., and the reader is then led on to the consideration of the special techniques and fields of the capstan, turret and automatic lathes.

A chapter on the methods of producing holes leads to the description of drills and reamers and drilling and boring machines, and this in turn leads to the consideration of the marking out process and the use of jigs and fixtures.

Milling is discussed at some length because of its great importance, and planing, broaching and gear cutting are then dealt with. A chapter is devoted to the grinding process and another chapter covers the allied processes of honing, superfinishing and lapping. The book concludes with a chapter on methods of measuring and gauging.

Throughout the book an endeavour has been made to lead the reader to realise the trend of modern production processes and to point out the advantages and drawbacks inherent in them.

It is hoped that the book will prove useful as a text-book for students working for the membership examinations of the engineering institutions, for the examinations of the City and Guilds of London Institute, and for the National Certificates in Engineering.

W. STEEDS.

PREFACE TO SECOND EDITION

The reception accorded to the first edition of this book encourages the author to believe that it has been found useful by the readers for whom it was written.

This edition differs little from the former, but the opportunity has been taken of correcting a few unimportant slips and of adding a few remarks in several places.

W. STEEDS.

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CONTENTS

Chapter 1

THE TESTING AND INSPECTION OF ENGINEERING MATERIALS

The materials used by engineers may be classified as (*a*) *Metallic*, and (*b*) *Non-metallic*. With a few exceptions, the former only will be dealt with in this book. They may be divided into (1) *Ferrous*, and (2) *Non-ferrous materials* ; in ferrous materials the principal constituent is iron, while non-ferrous materials contain little or no iron.

All metals possess in some degree the properties of elasticity, plasticity, ductility, malleability, toughness, brittleness, hardness, wear-resistance, and corrosion-resistance, but no metal possesses any one of them to perfection. These properties require definition, but complete and exact definition is very difficult and will not here be attempted.

Elasticity. An elastic material is one in which any deformation produced by the action of a force disappears entirely when the force is removed and in which the load-extension diagram (see p. 5) for a decreasing load coincides with that for an increasing one.

Plasticity. A plastic material is one in which small forces produce permanent deformations which increase more or less proportionally with the time of application of the force.

Ductility. A ductile material is one that can be drawn out into fine wires or rolled into thin sheets.

Malleability. A malleable material is one that can be hammered into thin sheets or small bars without cracking.

Toughness. A tough material requires considerable energy to fracture it and the fracture generally shows considerable local deformation.

Brittleness. A brittle material is one that breaks comparatively easily when it receives a sharp blow ; the fracture shows little or no local deformation.

Hardness. This is the property by virtue of which a material resists penetration or scratching by other bodies.

Wear-resistance is the ability to withstand abrasive action.

Corrosion-resistance is the ability to withstand the chemical action of acids, alkalis, oxidising gases, etc.

The engineer is concerned with all of the properties enumerated above and, in addition, he requires to have a knowledge of the mechanical strengths of materials, that is, their ability to withstand tensile, compressive, and shearing stresses, not only under simple unvarying loads but also under complex and fluctuating loads and under different conditions of temperature. In order to assess or measure these properties numerous testing machines and methods have been developed. Some of them are used only in laboratories while others have become standard

works practice; the former do not come within the scope of this book but, if the chapters on materials that follow are to be properly understood, the reader must have some knowledge of the tests whose results are extensively quoted therein. This chapter is designed to supply sufficient information for that purpose; for detailed information regarding testing machines and methods the reader is referred to the books listed at the end of this chapter.

The Tensile Test. This is a very old-established test and is probably the most widely used of any. Briefly it consists in applying a tensile load, i.e. a pull, to a specimen of material and measuring the loads at which fracture occurs or at which the material ceases to be elastic, etc.

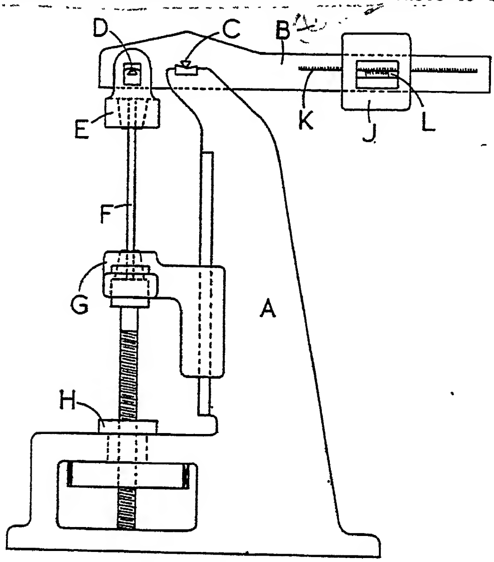


FIG. 1.

The details of the machines in which these tests are carried out is no concern of this book, but a very brief consideration of their fundamental principles is desirable.

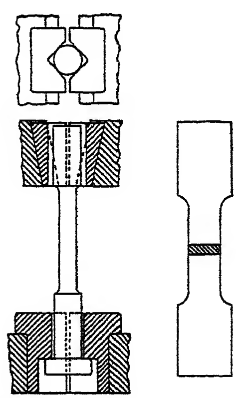
In Fig. 1 is shown a diagram of a single-lever testing machine. It consists of a column A, bolted to suitable foundations, on top of which a lever B is pivoted on a knife-edge C. A second knife-edge D supports the member E which is provided with means for gripping or holding the upper end of the specimen F that is being tested. The lower end of the specimen is held in similar "grips" carried in the saddle G which can slide up and down the machined face of the column A (or which is otherwise guided) being actuated by various means; a screw passing through a rotatable nut H is shown, but hydraulic rams or other means are quite common. Free to slide along the lever or beam B is a "jockey-weight"

J; by sliding this outwards (to the right) the pull applied to the specimen may be increased and the position of the jockey-weight provides a measure of the load applied to the specimen so long as the lever is "floating" and is not bearing against the stops provided to limit its motion to a reasonable amount. The lever is consequently furnished with a scale K which can be read against an index or vernier L carried by the jockey-weight. Large testing machines are usually provided with a compound lever system and the specimen may be arranged to lie horizontally instead of vertically. Other load measuring methods than the lever and jockey-weight are also used.

Small extensions of the specimen, such as occur while the material being tested remains elastic, can usually be accommodated by the tilting of the lever but any large extension must be taken up by lowering the saddle G; in many machines this can be performed by power.

In ordinary testing procedure the straining mechanism which operates the saddle G is set to work continuously at a constant rate and the jockey-weight is moved out along the lever to keep the lever balanced; this requires some skill. Alternatively the jockey-weight can be moved out by regular steps and the lever be restored to the horizontal as necessary by operating the straining mechanism and lowering the saddle G. The rate of straining has been shown to be generally unimportant in tests made at atmospheric temperatures, approximately the same results being obtained when the specimen is broken in a test occupying, say, 15 minutes as in a test occupying only 1 minute. For some ductile materials and for tests at high temperatures the straining rate is important (see p. 15).

Types of Specimen. Broadly speaking there are two types, (*a*) Round, and (*b*) Flat, as shown in Fig. 2. Round specimens are frequently machined all over and two alternative forms of end are shown; the enlarged end at the top is intended to be gripped in some form of wedge grip as indicated, while the shouldered end shown at the bottom is used in conjunction with split grips, the load being applied through the shoulders. Specimens with enlarged screwed ends are sometimes used and un-machined parallel rods are often used as specimens, the latter being gripped in V-shaped wedge grips. The flat specimen shown at *b*, and which is used for plate material, is generally un-machined, except where it is reduced in width. The British Standards Institution has laid down standard dimensions for tensile test specimens; these are set out in B.S.S. No. 18—1910.[1] The results obtained in a tensile test



(*a*) (*b*)

FIG. 2.

[1] Obtainable, price 2*s*., from the British Standards Institution, 28, Victoria Street, London, S.W.1.

depend to some extent on the shape of the specimen and the standard dimensions should not be greatly departed from, but, provided the parallel portion of the specimen is not too short in relation to its cross-sectional area, the variations in the test results consequent on slight changes in the dimensions of the specimen will not be very large. The use of very small specimens in miniature testing machines has greatly increased in recent years; in such things as welds it is not generally possible to obtain a full-sized specimen and the small specimen is imperative. A description of the Hounsfield miniature testing machine will be found in *Engineering*, Vols. CXXXI and CXXXVI.

Extensometers. While a material is elastic the extensions that occur in testing specimens are very small and special instruments, called extensometers, must be used for measuring them. The principle of a widely used type, the *Ewing*, is indicated in Fig. 3. A clamp A is secured to the specimen by screwing in two pointed screws at C; a similar clamp D is secured at E. The clamp D carries a microscope F and is connected to the upper clamp A by the rod G. Contact is maintained partly because the centre of gravity of the upper clamp lies to the right of the point C and partly by the spring H. Hanging from the clamp A is a rod L which carries a cross-wire J that can be brought into the field of view of the microscope by adjusting the screw K. When the points C and E move apart because of the extension of the specimen the cross-wire moves relatively to the microscope and the movement is observed on a graduated scale in the eyepiece. The head of the screw K is graduated and serves as a micrometer screw to calibrate the instrument.

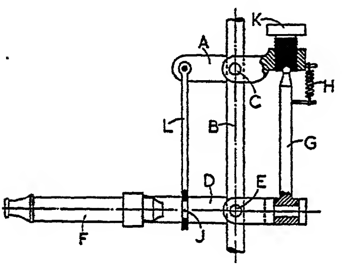
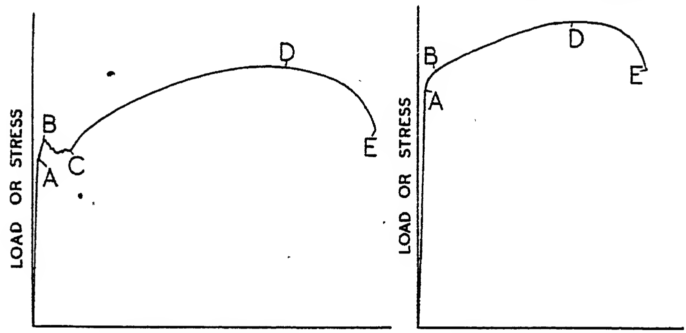


FIG. 3.

The distance CE over which the extensions are measured is called the *gauge length* and is, more or less, standardised, the common values being 2, 3, 3½, 4, and 8 in. To enable the gauge length to be accurately and easily determined when the extensometer is being placed on the specimen the clamps A and D are held by a rigid "gauge bar" until the screws C and E have been adjusted. The gauge bar must, of course, be removed before the specimen is loaded.

Load-Extension and Stress-Strain Curves. If corresponding readings of load and extension in a tensile test are plotted, a load-extension diagram or curve is obtained. Alternatively the *stress* (the load ÷ original area of the specimen) may be plotted against the *strain* (the extension ÷ gauge length). The diagram shown in Fig. 4*a* is typical of annealed mild steel, while that at *b* is typical of "cold-worked" mild steel (material

which has been "worked" or deformed at atmospheric temperature), most alloy steels, and many non-ferrous materials. Up to some point A, called the *limit of proportionality*, the extension or strain is directly proportional to the load or stress and the graph is a straight line. (In the figure the extensions up to the point A have been greatly exaggerated in order to separate the graph from the ordinate axis.) From A to B the extension increases more rapidly than in direct proportion to the load but the specimen is still elastic, so that if the load is removed the specimen will return to its original length. The stress corresponding to the point B is known as the *elastic limit*, but in commercial testing extensometers are rarely used and so neither the limit of proportionality nor the elastic limit are normally determined. In a mild steel specimen when the stress corresponding to B is exceeded a sudden "yield" or give occurs and the



(*a*) (*b*)

FIG. 4.

extension of the specimen suddenly increases to many times the elastic extension without any increase being made in the load, even, in fact, though the load may be reduced slightly. This is known as the *yield point* and the corresponding stress is one of the important results obtained in commercial testing. The yield point is indicated by a sudden drop of the lever of the testing machine or by a sudden reduction in the rate at which the jockey-weight has to be run out when the rate of straining is constant. Another method of detecting it is to set a pair of dividers to a suitable gauge length and to place one point in a centre-pop made somewhere near to the bottom of the specimen and to scribe a line on the specimen with the other point; the dividers are held in place as testing proceeds and the load at which the upper point is seen to scribe a distinct second line is taken as the yield load. After the yield has occurred the load must again be increased in order to produce any further extension and the graph is as shown until the maximum load is reached at D. In annealed mild steel the yield point is well marked, but in carbon and alloy steels and in most non-ferrous materials it is either very

indefinite or non-existent ; in these materials the load-extension diagram is as shown at *b* in Fig. 4, and the yield stress is sometimes defined as that stress at which the permanent set becomes equal to 0·5 per cent of the gauge length.

Up to the maximum load point D the cross-sectional area of the specimen has changed only very slightly because of the extension, but from the maximum load point onwards the extension becomes localised, a " neck " is formed, the load necessary just to keep the specimen extending becomes progressively smaller and smaller, and the load-extension diagram tails off until the breaking point is reached at E. It requires considerable skill in the manipulation of the testing machine to enable the part DE of the diagram to be obtained and in commercial testing no attempt is made to run the jockey-weight back and thus reduce the load after the maximum point has been reached. In " autographic " testing machines the load-extension diagram is drawn automatically as the test proceeds, either as a pencil trace on paper or, more accurately, by a spot of light falling on a photographic plate.

The stress corresponding to the maximum load point D is called the *maximum stress* or the *ultimate strength* of the material and is calculated on the *initial unstrained cross-sectional area of the specimen.* If allowance were made for the reduction in cross-sectional areas that occurs between the points D and E it would be found that the stress increased continuously right up to the breaking point. In some materials the load-extension graph is curved all the way from zero load up to the yield point, that is, there is no limit of proportionality ; also the greater the sensitivity of the extensometer used the lower is that limit found to be with all materials. Practically all materials also exhibit the phenomenon of " elastic hysteresis," that is, if they are loaded up to any stress within the " elastic limit " and are then unloaded, the extensometer readings being observed, then the unloading stress-strain curve will not coincide with the loading one until zero load is reached. In brittle materials very little permanent extension occurs and the diagram ends at a point corresponding to B in Fig. 4*b*.

Percentage Elongation and Reduction of Area. If, after a specimen has been broken, the two portions are put together and the distance L_1 between the two gauge points is measured, the percentage elongation may be found. It is defined as $100(L_1-L)\div L$ where L is the initial gauge length. Because the elongation that occurs after necking has set in is very localised, very different values of the percentage elongation will be obtained by taking different initial gauge lengths. Hence it is important that the gauge length be specified when the percentage elongation is quoted. If it is not then it must, generally, be assumed to be 2 in.

If the diameter D_1 of a circular specimen is measured at the point of

fracture then the percentage reduction of area can be calculated, being given by $100(D^2-D_1^2)/D^2$ where D is the initial diameter.

High values of the percentage elongation and, more particularly, of the percentage reduction of area are characteristic of ductile materials but the former is not a very reliable *criterion* of ductility. Two materials showing equal percentage elongations in the tensile test may show up very differently under other tests, such as bend tests (see below) and the Erichson test (see p. 12).

Proof Stresses. For materials in which the limit of proportionality is low and the yield point indefinite it is usual to specify proof stresses; these are the stresses at which the permanent set of a specimen, measured on a specified gauge length, does not exceed some stated percentage of that gauge length. A common value for the permissible permanent set is 0·1 per cent and the stress that just produces this is called the "0·1 per cent proof stress." Because some ductile materials go on extending for a considerable time after a load has been applied or increased before equilibrium is reached it is sometimes specified that the permissible elongation must not be exceeded within a specified time of the application of the load; 15 seconds is a common time.

Transverse Bar Tests. These are used chiefly for cast iron and consist in placing a bar of rectangular or circular cross-section on two supports and applying a load at the centre until fracture occurs. The minimum fracturing load and also, sometimes, the minimum deflection are specified. The English standard bars are $40 \times 2 \times 1$ in. and are cast and tested with the 2-in. dimension vertical and on a span of 36 in. The American and German standard bars are cylindrical. The bars are not machined before testing and the manner in which small variations in the dimensions shall be allowed for is laid down. A typical test result for average cast iron with the English bar is about 30 cwt. breaking load and about $\frac{3}{8}$ in. deflection at the centre.

Bend Tests. These are carried out in order to verify that material is sufficiently tough and ductile; they are made by placing the bar to be tested on two supports at a specified centre distance and then applying a load at the centre of the bar by means of a round-ended strut or former. The bar is required to bend, without the appearance of any cracks, until the angle included between its straight portions reaches a specified value. The supports are sometimes rigid and sometimes take the form of rollers but their radii, as well as the radius of the end of the former, must be specified in relation to the dimensions of the test bar. For circular bars up to $\frac{3}{4}$ in. diameter and for rectangular bars up to $\frac{3}{4}$ in. width the test can be carried out in a simpler manner by means of a former and a vice; the bar and former are held in the vice and the bar is bent over the former by hitting it with a hammer. The diameter of the former is commonly made equal to twice the diameter or width of the bar. The

bend test is much used for testing welds as it shows up defects better than most other tests. For a full consideration of the bend test the reader is referred to a paper by L. W. Schuster in *Proc. I. Mech. E.*, 1935.

Impact Tests. A high value of the yield-point stress or of the ultimate strength is not always an indication that a material is suitable for withstanding the loads it may be subjected to in service. If the loads are applied suddenly, as blows, it will sometimes be found that a material giving very high values in the tensile test will fracture under much lighter blows than a material giving poorer tensile test results. To determine the suitability of a material under these impact conditions various forms of impact test have been evolved. Only two are of any great importance, namely, the *Izod* and the *Charpy*, and in Great Britain only the Izod is at all widely used.

The Izod Test. The specimen is commonly shaped as shown in Fig. 5, being designed so that four tests can be made on each specimen.

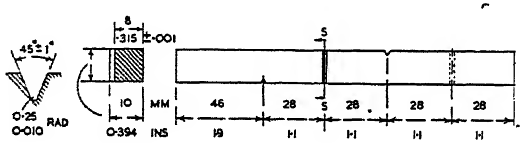


FIG. 5.

The latter is held in the vice of the testing machine as indicated in Fig. 6, the centre of the notch being set level with the vice jaw by means of a simple gauge. The pendulum A of the machine is then released from the catch B, on which it has previously been placed, and swings over so that the striker E hits the specimen, as shown in the inset sketch, and fractures it. Since it requires energy to fracture the specimen the pendulum will swing past the vertical to some angle θ_1 that is smaller than the angle θ from which it started at the other side. The difference $\theta-\theta_1$ is a measure of the energy expended in fracturing the specimen and can be read off the scale F against the idle pointer C. The latter is moved across against a projecting pin of the pointer D at the beginning of the test and remains in the position to which it is pushed as the pendulum swings over. The potential energy of the pendulum when it rests on the catch B is 120 ft.-lb. The zero of the scale lies at the point reached

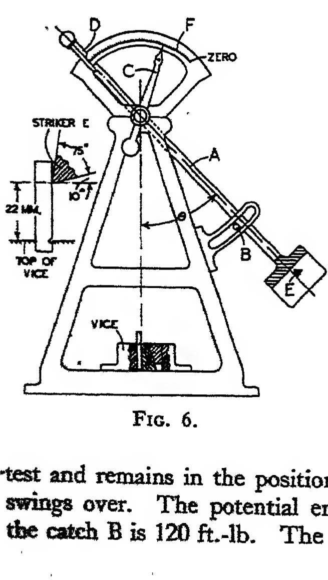


FIG. 6.

by the pointer D when the pendulum is released without there being a specimen in the vice.

The Charpy Test. This is similar to the Izod in general principle, but the specimen is mounted as a beam as shown in Fig. 7 instead of as a cantilever. The specimen is 10 mm. square in section as for the Izod test and the Izod form of notch is sometimes used, but the form shown in Fig. 7 is also used. The striker of the pendulum is also arranged so that it is approximately coincident with the centre of percussion of the pendulum.

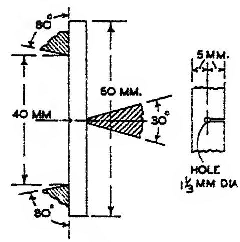


FIG. 7.

The British Standard shapes and dimensions for Izod and Charpy specimens are laid down in B.S.S. No. 131—1933.

The results obtained for a given material in either the Izod or the Charpy test will only be comparable when the specimens used are identical in size, shape of notch, etc., and it is therefore important that standard specimens should be used.

Hardness Tests. Numerous methods and machines for testing the hardness of materials have been tried but only a few are in extensive use, namely, the *Brinell*, *Vickers diamond* (V.D.H.), *Rockwell*, and *Shore scleroscope*.

The Brinell Test. This is one of the oldest and also one of the most widely used hardness tests and consists of pressing a hard steel ball, usually 10 mm. in diameter, into the specimen by applying a standard load, usually 3,000 kg., thereby producing a depression in the specimen. The diameter of this impression is measured by means of a specially graduated microscope and the Brinell hardness number may then be calculated from the equation,

$$\text{Brinell number} = \frac{\text{Applied load (kg.)}}{\text{Spherical area of the impression (sq. mm.)}}$$

$$= \frac{P}{1{\cdot}571D(D-\sqrt{D^2-d^2})}$$

where D = diameter of ball,

d = diameter of impression,

P = applied load.

Usually, however, the hardness number is looked up against the appropriate value of d in tables.

It has been shown that provided the load is made proportional to the square of the ball diameter the impressions produced will give a constant hardness number on a given specimen. In practice the standard 10-mm. ball and 3,000-kg. load are departed from only for tests on thin sheets and soft material; the British Standard Specification dealing with the

Brinell test (No. 240, Pt. 1—1937) provides for a number of different sizes of ball and gives the corresponding appropriate loads. For very hard materials which would give a Brinell number greater than about 500–600 a tungsten-carbide ball has to be used, because the deformation of a steel ball becomes sufficient to affect the results appreciably.

Special machines, some of them power operated, have been developed for making the Brinell test, which is widely used in engineering works as an acceptance test for discriminating between satisfactory and unsatisfactory material.

The Vickers Diamond Test. This also consists of pressing an indenter into the specimen by means of a standard load. The indenter is, however, a diamond pyramid (and the hardness given by the test is sometimes referred to as the D.P. hardness) and has a square base and a facet angle of 136 degrees. It makes a square pyramidal impression in the specimen and the diagonals of this impression are measured with a microscope, which is usually part of the machine used; the mean value of the readings gives the hardness number from the equation,

$$\text{V.D.H. or } H_D = \frac{\text{Load}}{\text{Surface area of impression}} = \frac{2P \sin \theta/2}{d^2}$$

where P=load in kg., d=mean diagonal in mm., and θ=angle of the diamond pyramid. The British Standard loads (see B.S. 427 : 1931) are 5, 10, 20, 30, 50, 100 and 120 kg. The load used should be stated, thus, $H_D/50=x$, $H_D/20=y$. New forms of diamond indenter have been developed recently for testing brittle materials and very thin sheets. (See *Engineering*, January 31, 1941.)

The *Firth "Hardometer"* uses a pyramidal diamond just like that used in the Vickers machine and measures the width across the resulting impression so that it gives the same hardness numbers as the Vickers.

The Rockwell Test. This also consists in pressing a diamond indenter into the specimen under a standard load, but the diamond is conical with a rounded point and the *depth* of the impression is measured while the load is on, and is used to give the hardness number. In order to eliminate the effects of backlash and spring in the machine and its integral measuring instrument a small or *minor* load of 10 kg. is first applied and the measuring instrument is set to zero, then a large or *major* load is applied and the hardness number is read off the instrument. The major load used with the diamond indenter is generally 150 kg. and the corresponding hardness number is referred to as "Rockwell C." A $\frac{1}{16}$-in. diameter ball is also used as an alternative indenter with a major load of 100 kg. and a separate scale is provided on the measuring instrument for use with it. The corresponding hardness is referred to as "Rockwell B." Other indenters and major loads are sometimes used, the corresponding hardness numbers being designated by other letters,

and it is important that the proper letter applying to the particular indenter and major load used should be quoted.

In the *Monotron* hardness test, which is used to some extent in America, a $\frac{3}{4}$-mm. diameter diamond ball is caused to penetrate the specimen to a constant depth of 0·045 mm. and the *load* required to produce this penetration is used to give the hardness number by dividing it by the spherical area of the impression. Thus in this test and in the Rockwell, as opposed to the Brinell, Vickers, and Firth tests, the elastic deformation under the applied load is taken into account in arriving at the hardness number.

The Shore Scleroscope. This is an instrument by means of which a small hammer weighing about $\frac{1}{12}$ oz. is dropped from a height of about 10 in. on to the specimen and the height of its rebound is used to measure the hardness, being measured on a scale against the top of the hammer at the highest point of its rebound.

The Herbert Pendulum Test. This, although not very widely used commercially, has certain advantages over the other tests, one important one being that it tests to some extent the " work-hardening " properties of the material being tested. The pendulum weighs 4 kg. and is shaped as indicated in Fig. 8. It is supported on a ball 1·0 mm. diameter whose position can be adjusted so as to bring the centre of gravity of the whole mass 0·1 mm. below the centre of the ball. At the top is a bubble tube and a scale graduated with 100 divisions. The instrument can be used in two distinct ways. First, by placing it on the specimen in a tilted position so that the bubble reads zero and then releasing it so that it swings over. The reading of the bubble at the end of the first swing across is then taken as the " scale hardness " number. This consequently ranges from 100 down to 0. The second method is to place the instrument on the specimen with the bubble reading 50 and to set it swinging. The time in seconds required for ten single swings is then taken as the " time hardness " number. It also ranges from about 100 for glass down to 3 for lead.

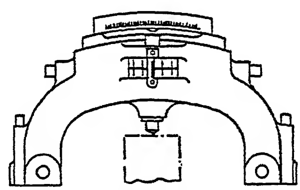


FIG. 8.

The chief advantages of the Vickers, Firth, Rockwell, and Scleroscope tests over the Brinell are that they can be used on very hard material, whereas in the Brinell test the upper limit to the hardness is set by the hardness of the ball, and, secondly, that they do not damage the surface of the specimen so much.

The hardness numbers given by the various tests do not bear any simple relation to one another and conversion charts and tables, though published, should be used with caution, the conversions being accepted as approximate only.

Ductility Tests. In press-tool work (see Chap. 6) the ductility of the material is a most important factor and many attempts have been made to devise a test which will give a reliable indication of the suitability or unsuitability of material for drawing operations in press-tools. The only test that is at all widely used, however, is the *Erichson cupping test.* This is carried out in a standard form of machine, the test-piece A (Fig. 9) being gripped between the holder B and die C. After the holder has been tightened on to the specimen it is slacked back a constant amount (0·05 mm.) to give the specimen freedom to draw and the cupping tool D is then pressed into the specimen until cracks appear on the dome of the cup, these being observed in the mirror E. The depth of cup at fracture is read off the scale of the machine and is a measure of the drawing quality of the material. Fig. 10 shows Erichson's

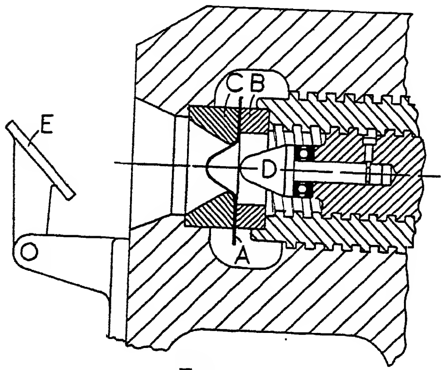


FIG. 9.

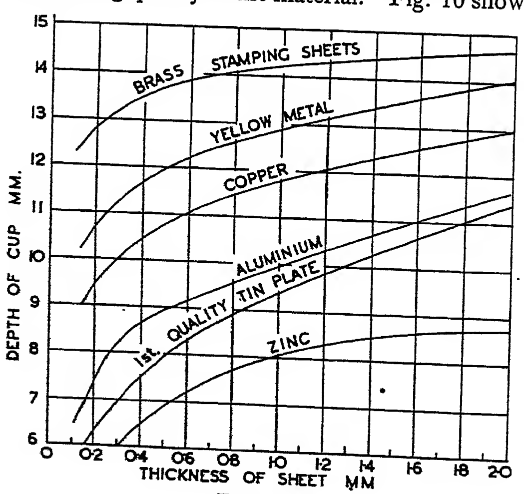
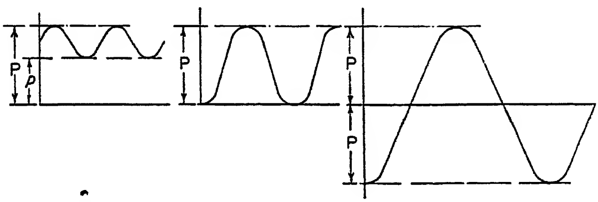


FIG. 10.

standard curves giving the depth of cup for various thicknesses of sheet and kinds of material. For a full consideration of tests for determining the drawing qualities of material the reader is referred to three papers on "Cold Pressing and Drawing" by (*a*) H. J. Gough and G. A. Hankins, (*b*) C. H. Desch, and (*c*) G. Sachs in *Proc. I.A.E.*, Vol. XXIX, 1934–5.

Fatigue Testing. It has been known for nearly a century that a bar of metal that is subjected to a load which is applied and removed a large number of times, or which fluctuates between two limiting values, can be fractured despite the fact that the maximum value of this load may be considerably less than the value corresponding to the elastic limit in an ordinary tensile test. This phenomenon has come to be denoted by the term " fatigue."

Three conditions of loading may be distinguished and are indicated in Fig. 11*a*, *b*, and *c* ; these are called respectively *fluctuating*, *repeated*, and



(*a*) (*b*) (*c*)

Fig. 11.

alternating or *reversed* loads. The fluctuating load may vary between two positive limits as shown, when it may be called a *pulsating load*, or between a positive and a negative limit. The repeated and alternating loads are merely special cases of the fluctuating load.

Considering the alternating type of loading, if a large number of tests are made on a corresponding large number of specimens in which the range of load 2P is gradually reduced and if the number of reversals necessary to produce fracture are plotted against the range of stress, the graph will be somewhat as in Fig. 12. This implies that fracture will never occur provided that the range of stress is kept within some value *t*, but, of course, from the nature of the test, it is not possible to say whether this is actually so or not.

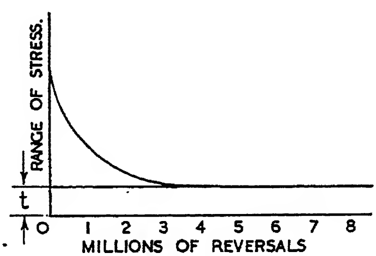


Fig. 12.

In practice the limiting range of stress that will not produce fracture in 10,000,000 reversals is generally taken as the fatigue strength of a material. The results depend on the type of machine used to some extent, but similar types of machine give similar results.

Numerous machines have been developed to test fatigue strengths but only two types are of sufficient importance to be described here ; they are the Wohler and the Haigh machines.

The Wohler Type Machine. In this the specimen is circular in cross-section and is loaded as a cantilever as shown in Fig. 13, being secured in a rotating chuck at one end and loaded with a dead weight at the other end. As the specimen rotates so the stress alternates between tension and equal compression once during each revolution. To reduce the variation in the applied stress from the inside to the outside the specimen is sometimes made hollow as shown, the wall thickness being made quite small. The maximum stresses in the specimen occur at the section SS where the transition curve from the small diameter to the larger one commences, and this is held by some to be a drawback to this form of test. The drawback can be avoided by using "four-point" loading as indicated in Fig. 14. This loading gives a pure bending moment on the centre portion of the specimen and eliminates the shearing stress that exists in the cantilever specimen.

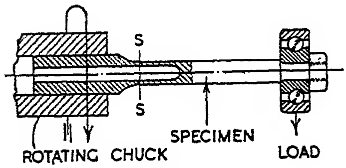


Fig. 13.

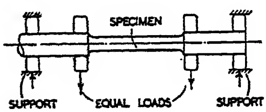


Fig. 14.

The machines used for making this test are very simple and embody counters to count the number of reversals and trips to stop the machine when the specimen fractures.

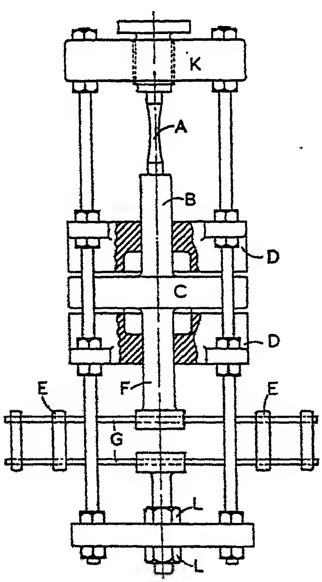


Fig. 15.

The Haigh Machine. In this machine, which is shown diagrammatically in Fig. 15, the specimen A is secured at its lower end to the stem B of an armature member C which is situated between two electro-magnets DD. The windings of the latter are excited by alternating current and thus an alternating stress is applied to the specimen. A specially wound alternator is used in order to get a sine-wave variation of load and stress and, in order to eliminate inertia effects due to the mass of the armature, the bottom stem F is connected to springs G whose effective stiffness can be adjusted by moving the clamps E in or out. This is done until, with no specimen in the machine, resonance is obtained between the natural frequency of the armature spring assembly and the alternating pull applied by the electro-magnets. Provided the air-gaps

between the armature C and magnets DD are made equal by moving the upper end of the specimen up or down relative to the yoke K, and that equal voltages are applied to the magnet windings, the upward and downward loads applied to the specimen will be equal, i.e. the loading will be alternating or reversed as in Fig. 11*c*. If a fluctuating load is required the mean stress is applied through the springs G by adjusting the nuts L, and the electro-magnets provide the variation on each side of the mean stress. Calibration of the machine is a somewhat complex procedure which need not be considered here; for full details the reader is referred to *Engineering*, November 22, 1912, and to *Journal Institute of Metals*, No. 2, Vol. XVIII, 1917.

One of the important facts brought out by fatigue testing is the importance of quite small imperfections in the surface finish of a specimen. Such imperfections, scratches, file or tool marks, etc., and also keyways, sharp internal corners, small holes, and sudden changes of section, produce concentrations of stress which greatly reduce the fatigue strength of the piece unless the material of which it is made is sufficiently plastic to redistribute the stresses. It has also been found that the presence of any substance tending to produce corrosion of a material will greatly reduce its fatigue strength or, putting it another way, fluctuating or alternating stresses greatly promote the corrosion produced by any surrounding medium. Consequently fatigue tests are frequently carried out with the specimen surrounded by such corrosive medium.

Tensile Tests at High Temperatures. The behaviour of metals in tensile tests at elevated temperatures is very complex and can only be just mentioned here. The ultimate strengths of steels generally show a slight decrease as the temperature at which the test is carried out rises up to about 200° C., there is then an increase until at some temperature between 300° and 400° C. the strength reaches a maximum, being greater than at atmospheric temperatures, after which there is a steady decline. The temperature giving the maximum ultimate strength depends on the speed of testing, i.e. the rate of straining; at temperatures up to that giving the maximum strength the lower the rate of straining the higher will be the strength, but at temperatures above that giving the maximum strength the reverse is true. A variation in the straining rate from 0·001 to 0·6 in. per minute on a 2-in. gauge length at a temperature of 500° C. increased the ultimate strength of a 5 per cent nickel steel tested by Bailey and Roberts [1] from 15 to 22 tons per sq. in., while in a test at 300° C. the lower straining rate gave a strength of 38 tons per sq. in. while the higher straining rate gave only 30 tons per sq. in. This shows the importance of the straining rate in tensile tests made at high temperatures.

[1] "The Testing of Materials for Service in High Temperature Steam Plant," R. W. Bailey and A. M. Roberts, *Proc. I. Mech. E.*, February, 1932.

Creep Testing. If a steel specimen is loaded to a constant stress at an elevated temperature elongation of the specimen sometimes goes on for very long periods, but the rate at which the elongation increases generally falls off fairly soon and reaches a low value. This is indicated in Fig. 16. If the elongation or strain-time graph does become parallel to the time axis, then, of course, extension of the specimen has ceased, but it is never possible to say whether this is actually so or not because the means used for measuring the extension cannot indicate the almost infinitesimal extensions involved. According to some experimenters, there is, for each stress and material, a certain temperature below which the strain-time graph does become " horizontal " (or, put in another way, there is, for any given *temperature* of test, a *stress* for which the graph does become horizontal); this stress is called the " limiting creep stress " for this material and temperature. Because of the limitations of the extensometers used it is impossible to be sure that the creep has ceased and so it is generally assumed that if the slope of the strain-time curve reaches an arbitrary low value the graph will become horizontal and the corresponding stress is taken as the limiting creep stress. Some authorities, however, maintain that the graph never does become horizontal, others that although it may become horizontal it may, subsequently, begin to rise again, i.e. elongation may recommence and that consequently there is no such thing as a limiting creep stress. If this is true, then all that can be done is to arrange the working stress so that the rate of elongation or creep is sufficiently low to make the time required to produce serious deformation greater than the expected life of the part. Since it is no practicable to wait for years for the results of tests giving the creep rates under actual working conditions efforts have been, and still are, directed towards finding some form of " short " test which will enable the creep under working conditions to be predicted. The subject has not yet reached sufficient finality to justify its being considered further here, and for information about it the reader is referred to the numerous papers that have been published in the proceedings of the technical institutions during the last twenty years.

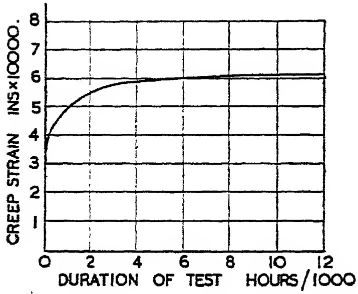


Fig. 16.

One other aspect of the behaviour of materials at high temperatures must be mentioned; it is the tendency to scaling and growth. In connection with this the reader is referred to a paper by Dr. W. H. Hatfield in *Proc. Inst. Fuel,* March 24, 1938. This paper gives the properties of a number of steels not only as regards scaling but also as

regards creep strengths. It also has a comprehensive bibliography of the subject.

Magnetic Methods of Inspection. The detection of cracks, blowholes, slag inclusions, and other faults by magnetic methods has now become a commercial process. The methods depend on the fact that the magnetic susceptibility in the region of a fault is inferior to that of the surrounding material and so, when a magnetic flux is set up in the specimen, the fault acts as a discontinuity or air-gap and modifies the flux distribution. The resulting distortion of the magnetic field may be detected in several ways ; for example, by means of a small pivoted bar-magnet or of a search coil included in a suitable electric circuit, but the most widely used method is by means of very finely divided iron particles or " iron dust." When such iron dust is sifted gently over the surface of the magnetised specimen it adheres in the region of a fault and thus indicates the presence of the fault. An alternative and better way of applying the iron dust is to suspend it in a fluid, usually paraffin, and to pour this fluid gently over the specimen or to dip the specimen into the fluid. To be effective the direction of the magnetising flux must be approximately perpendicular to the plane of the fault, and to obtain this various methods of setting up the flux are used according to the probable placing of the faults. One method is to place the object between the poles of an electro-magnet ; the direction of the flux in the object can then be varied by moving the object into various orientations relative to the pole-pieces of the magnet. A second method is to pass an electric current through the object and this method is used in testing bar material in which, due to the rolling process by which it is produced, the faults are mostly parallel to the axis ; the current produces a circumferential or circular magnetisation and thus makes the flux approximately perpendicular to the probable faults. Machines for testing bars up to 12 ft. long and 3 in. diameter are now obtainable and bar material for important components such as aero engine parts is all inspected in such machines.

The magnetic method of inspection, being non-destructive, is commonly applied to finished parts and is effective in showing up surface cracks which are invisible to the unassisted eye. Such surface cracks are not uncommon in the wire used for making coil springs and sometimes do not develop until after the spring has been coiled and heat treated. Consequently important coil springs are generally inspected magnetically after manufacture. The test also shows up surface cracks due to local overheating during grinding—a common defect—but it is not very effective for deep seated faults nor, of course, with non-magnetic materials.

Other Methods of Crack Detection. A very old method of detecting small cracks is to heat the object in an oil bath and, after removal,

clean it thoroughly and coat it with whitewash ; if there are any surface cracks oil will gradually exude from them and will stain the whitewash, thus indicating the fault.

A basically similar process is sometimes used in modern machine shops where machine parts, for example I.C. engine valves, are immersed (usually only the head and an inch or so of the stem) in an acid solution of cuprous chloride for a minute or two and on removal are washed in water and cleaned by rubbing moderately with a rag. The rubbing removes the deposit of copper from the surface of the part but not from any cracks and the latter are consequently shown up.

A much more elegant method is also being extensively used for detecting cracks in die-castings and similar articles. The method, which has been developed by Colloidal Research Laboratories, consists in immersing the article in a bath of special fluid and then examining it in ultra-violet light. The fluid has the properity of being highly phosphorescent in this light and, being trapped by the cracks, makes them appear brilliantly white, thus showing them up very distinctly.

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Chapter 2

FERROUS MATERIALS

The principal ferrous materials used in engineering may be grouped under the following headings:

1. Pig-iron.
2. Cast iron (C.I.).
3. Wrought iron (W.I.).
4. Mild steel (M.S.).
5. Carbon steels.
6. Alloy steels.

Pig-iron is the starting point in the production of all the other ferrous materials and is itself obtained by smelting iron ores which contain one or more of three compounds of iron, namely, Fe_2O_3 (hematite), Fe_3O_4 or $FeO.Fe_2O_3$ (magnetite), and $FeCO_3$ (siderite), as well as impurities of metallic and non-metallic kinds. Ores vary widely in composition, iron content, and in the facility with which they can be smelted. Some ores are rich in iron and are easily smelted, others are so poor that they are commercially unworkable, while others contain elements that make the smelting process difficult.

Practically all iron ore is smelted in *blast furnaces*; these are tall, slightly conical structures lined with refractory materials and provided with equipment for charging in ore and other materials at the top; with a ring of holes, called *tuyeres*, near the bottom through which air is blown; with suitable holes below the level of the tuyeres through which the slag that is formed by the incombustible impurities in the ore can be drawn off, and with a hole or spout at the bottom through which the molten iron that is produced is drawn off at intervals. Coke is used to provide the necessary heat and limestone to act as a flux and make the slag fluid at the temperatures reached in the furnace. The three materials coke, ore, and limestone, are charged into the furnace in rotation. The molten metal is run off into moulds formed in a bed of sand, giving *sand-cast pig-iron* or into metal moulds—usually arranged as part of a conveyor system—which gives *machine-cast pig-iron.* The air blown through the tuyeres is sometimes at approximately atmospheric temperature, and the pig-iron is then known as *cold blast* iron, but usually is heated to between 700° and 900° C., which gives *hot blast* iron. The former is usually low in silicon and the latter is high in that element. A third variety of pig-rion is *hematite pig*, being smelted from hematite ore; it is usually very low in sulphur and phosphorus.

Pig-iron is from 92 to 97 per cent iron, the remainder being carbon, silicon, manganese, sulphur, and phosphorus. Of these elements carbon is the most important and may be present in three distinct forms:

(*a*) combined with the iron as a complex compound, (*b*) combined with the iron as iron carbide, and (*c*) as graphite or free, uncombined carbon. The combined carbon varies in amount from as low as 0·25 up to as high as 3·5 per cent and the graphitic carbon from as high as 4 per cent down to almost zero. Pig-iron in which all the carbon is present in the combined form has a whitish fracture, is hard, brittle, and almost unmachinable, whereas pig-iron containing large amounts of uncombined carbon has a greyish fracture, is soft and easily machined. Silicon is next in importance to carbon in its effect and is present in percentages ranging from 0·5 up to 4·0. It has the effect of freeing the carbon so that, in general, the higher the silicon content the greyer the iron. Sulphur is always present, the percentage varying from 0·02 up to 0·4 or more; it tends to harden the iron but the extent of this action is dependent on the amount of manganese present. Manganese occurs in percentages from 0·5 up to 1·5; it combines with any sulphur present to form manganese sulphide (MnS) and this prevents the sulphur from hardening the iron. Excess of manganese beyond that required to combine with the sulphur has a direct hardening effect on the iron. Manganese makes iron more fluid at any given temperature above the melting point and thus promotes sound castings. Phosphorus also makes iron fluid to a much greater extent than manganese does, but phosphorus makes iron brittle and produces porosity and sponginess; hence it is always kept fairly low, generally below 0·3 per cent, except for intricate castings where strength is a secondary consideration.

Pig-irons are commonly classified in six groups. No. 1 pig contains the most free carbon and the least combined carbon, and No. 6 contains practically no free carbon. Nos. 1–4 are grey irons, No. 5 is mottled, and No. 6 is white. Pig-irons are now marketed to conform to definite chemical analyses and with silicon contents varying from 0·5 to 4 per cent in steps of 0·25 per cent. Pig-irons containing nickel and chromium for the production of alloy or high-duty cast irons can also be obtained.

Cast Iron. This is essentially pig-iron which has been modified in structure by re-melting in a cupola (see p. 90) and casting into moulds. Steel scrap is frequently added to the pig-iron and alloying elements may also be added. Cast iron is considered more fully in a subsequent section.

Wrought Iron. This is iron from which nearly all the carbon, and most of the sulphur, phosphorus, etc., has been removed by a process called *puddling*. It always contains some slag, up to possibly 2 per cent, in the form of fine filaments. In the puddling process pig-iron is placed on a layer of iron oxide (frequently the scale formed on the surfaces of forgings is used) and is melted by passing the products of combustion of a coke fire over it. Part of the carbon and most of the impurities are

oxidised and removed from the molten pig and, since the melting temperature of iron increases as the carbon content is reduced, the iron becomes a pasty mass. This is worked or *puddled* by means of long bars and finally rolled up into balls or *blooms* which are removed from the furnace and hammered under a steam hammer, which welds all the particles of iron together and also squeezes out a large proportion of the slag that is trapped in the bloom during the puddling. The hammered blooms are subsequently rolled into bars and it is then that the remaining slag is rolled out into filaments. Wrought iron thus has a definite " fibre " and shows different tensile strengths when tested along and across the fibre. Wrought iron is very malleable, forge-welds better than any other material, and resists atmospheric corrosion better than mild steel does. It is, however, more expensive than mild steel and is not now very widely used.

Steels. These may be roughly defined as alloys of iron and carbon in which the percentage of carbon ranges from almost zero in mild steel, up to 1·8 in some tool steels. Steel is made by numerous processes but the most important are :

1. The cementation process.
2. The crucible process.
3. The open hearth process.
4. The Bessemer process.
5. The electric process.

The last three, which are by far the most widely used, can be subdivided into

(*a*) Acid processes ;
(*b*) Basic processes.

The first two processes are now confined to the production of high quality steels in small quantities for special purposes and as, in these processes, it is not practicable to reduce the sulphur and phosphorus contents, the materials used must be comparatively free from those impurities, and Swedish materials, which are very low in them, are usually employed. In the cementation process bars of wrought iron are packed in charcoal and heated so that carbon enters into solution in them, although they never become molten. The distribution of the carbon is not uniform, the percentage decreasing from the outside to the inside. After this treatment the surfaces of the bars are covered with blisters (caused by the liberation of carbon monoxide formed by the combination of the carbon with the oxygen contained in the slag in the bars) and the product is known as *blister* steel. More uniform distribution of the carbon is obtained by reheating the bars and by welding several bars together under a hammer, thus giving *shear* steel. Crucible steel is made by melting Swedish pig-iron, wrought iron, and cemented bars in crucibles. It is only used for high-grade products such as cutting tools.

In the open hearth process a mixture of pig-iron and steel scrap or iron ore is melted in a *regenerative furnace.* This is a furnace in which the heat of the gases passing out is used to pre-heat the air used for the combustion of the fuel and thus to enable extremely high temperatures to be reached. Iron ore is also charged into the furnace when the initial charge has become molten. The carbon and the impurities are oxidised, the latter passing into the slag. In general carbon, manganese, and other elements have to be added subsequently in order to obtain the required composition and to get rid of iron oxides. In the acid open hearth process the furnace lining is a siliceous material and there is no elimination of phosphorus ; hence the original charge must not contain a higher percentage of phosphorus than will be admissible in the final product. In the basic open hearth process the furnace lining is of basic material and lime is charged into the furnace to prevent the slag from becoming acid ; phosphorus is reduced in this process which is thus suitable for materials containing high phosphorus contents. These remarks apply also to the Bessemer and the electric processes which may be either basic or acid. Basic open hearth steels and Bessemer steels are generally regarded as being somewhat inferior to acid steels and are not extensively used for the production of high-grade alloy steels ; they are, however, very widely used for structural and similar steels, especially abroad. Present day acid open hearth steels are very little inferior to electric steels, which have hitherto been regarded as the best obtainable, and in many cases have replaced them. Steel makers can now control the grain-size of open hearth steel with considerable exactness.

In the Bessemer process pig-iron and steel scrap are melted in cupolas and the molten metal is transferred to *converters.* In the latter air is blown through or on to the surface of the molten metal, so that the impurities and some of the carbon are oxidised and removed. It is the oxidation of the impurities, particularly the silicon, that provides the necessary heat to maintain and increase the temperature of the metal while it is in the converter. As most of the carbon and manganese are removed during the blowing process these elements have to be added in order to obtain the desired composition.

The additions of manganese and carbon are generally made in the form of *spigeleisen* or of *ferro-manganese.* The former contains up to 35 per cent of manganese and 6 per cent of carbon and the latter about 7 per cent of carbon and up to 80 per cent of manganese. The manganese is added in order to eliminate iron oxides as far as possible, since it reacts with those oxides, the percentage of which must be kept below 0·1 per cent. This operation is known as "killing" the steel and is sometimes done by means of aluminium. In general practice acid steels are killed in the furnace and basic steels in the ladle. The first method is the easier to control and gives cleaner steels, hence acid steels are used for making the expensive alloy steels and for steels that are required to

withstand shock loads. The presence of iron oxide and of non-metallic inclusions of all kinds tends to produce cracks in steels which are quenched to harden them. Basic steels are most suitable for use in the soft state and where shock loads are absent. Basic steel for structural purposes is only " semi-killed." Bessemer steels usually contain more iron oxide than either open hearth or electric steels.

The electric furnaces used for steel making are of two kinds : (1) Arc furnaces, (2) High-frequency induction furnaces. In the former the heat for melting the charge is produced by striking an arc between electrodes suspended from the roof of the furnace and the charge itself in the hearth of the furnace. The electrodes are made either of graphite or of amorphous carbon, the latter being cheaper but brittle and hence liable to introduce carbon into the charge; they are also poorer conductors of electricity. The hearth is lined with either a basic or an acid lining but the basic lining is the more common one. The furnace roof is almost always lined with silica bricks or with high alumina firebricks. The furnace is charged with pig-iron and steel scrap and the refining of the charge proceeds in two distinct stages. These need not be mentioned except to remark that in the first stage carbon, silicon, and manganese are removed and a black slag is produced, while in the second stage ferro-manganese or ferro-silicon, lime, and fluorspar are added to make the furnace conditions reducing, and the sulphur and absorbed gases are eliminated. During this stage a white slag is produced. Carbon in the form of coke or anthracite is then added to re-carburise the metal and the required alloying elements are introduced. The final composition of the steel can be controlled accurately and the process enables consistent results to be obtained. The operating costs are relatively high but the process is eminently suitable for the production of high grade alloy steels.

The high-frequency induction furnace is used for the production of steel by melting down a charge whose constituents will give the desired composition to the resulting metal. Although refining is possible, and is occasionally done, the process is usually merely a melting one, analogous to the crucible process but possessing the great advantage that the melting conditions are such that oxidation and contamination of the charge by sulphur, etc., are practically eliminated. It is particularly suitable for the production of chromium and vanadium steels in comparatively small quantities. The arc furnace also can be used merely to melt a charge if required, but it is not suitable for small quantities or intermittent operation.

The properties of steel can be changed tremendously by varying its composition and the heat treatment it is given, but these effects will be more easily understood if the structures of metallic alloys are first considered.

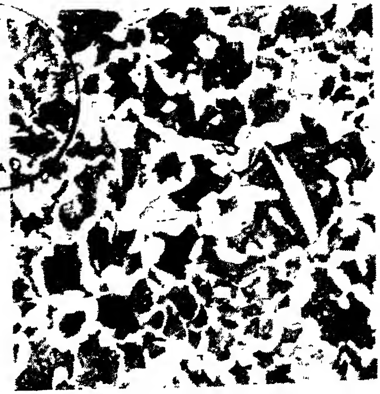
The Structures of Metals. All metals are crystalline in structure and when suitably polished and etched with a reagent the boundaries of the crystal " grains " can be seen, in a microscope giving a magnification

of 50–100, as a network of dark lines on a light background as shown in Fig. 17*a*. The appearance depends largely on the method of lighting up the surface of the specimen ; if *normal* illumination is used, in which the direction of the light is normal or perpendicular to the surface, the appearance will be as described, but if *oblique* illumination is used the appearance will be that of a dark surface with a network of light lines. Normal illumination is generally used.

In a pure metal all the crystals will be similar in appearance although they may actually differ in physical properties. Pure iron, for example, is known to exist in at least four different and distinct forms and these have been labelled the α, β, γ, and δ forms ; consideration of the nature of these differences is, however, beyond the scope of this book.

When an alloy is examined, different kinds of crystal grains will generally be seen as in Fig. 17*b*; for example, an alloy of iron and carbon containing about 0·2 per cent of carbon and which has been cooled slowly from the molten state will show a structure consisting chiefly of white grains but having some darker ones. The white grains are pure iron and are called *ferrite*, while the darker grains are *pearlite*. The term " ferrite " is used in preference to " iron " because when other elements besides carbon are present the white grains may contain those elements in solution and so may not be merely iron ; they may also contain a very small percentage of carbon. The term pearlite arises from the fact that as a specimen in which such grains occur is turned around under the microscope those grains exhibit colourings similar to those of mother-of-pearl. If the pearlite grains are examined under a microscope giving a magnification of 250 or more, they will appear as in Fig. 17*c*, being composed of black and white strips or layers. The white strips are again ferrite while the black strips are *cementite*, which is iron carbide (Fe_3C). Ferrite is soft, its Brinell number being about 100, and its strength is only moderate. Cementite is, however, very hard, too hard to be measurable by the Brinell test ; its diamond pyramid hardness is about 1,000 and its strength is comparatively great. Thus the pearlite grains are harder and stronger than the ferrite grains and, broadly speaking, the greater the proportion of pearlite the harder and stronger the alloy will be ; on the other hand, the ductility will be lower. As the percentage of carbon in an iron-carbon alloy is increased so the proportion of pearlite grains will increase and the proportion of ferrite grains will decrease until, when the percentage of carbon is 0·89, all the grains will be pearlite. When the percentage of carbon is greater than 0·89 the structure will show either dark bands round the pearlite grains or dark, almost black, grains intermingled with the pearlite grains. This black constituent is " free " cementite and as it increases in amount so the strength of the alloy will gradually fall off. When the percentage of carbon is greater than about 2, and particularly when other elements such as silicon are present, free carbon in the form of graphite will be seen in the structure.

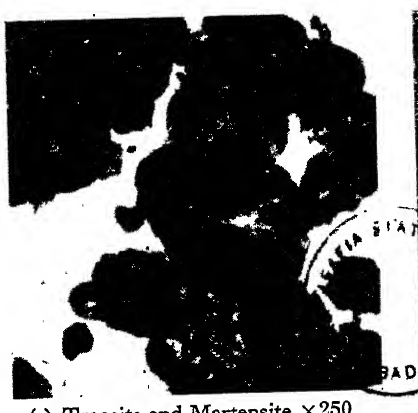
(*a*) Ferrite ×100.



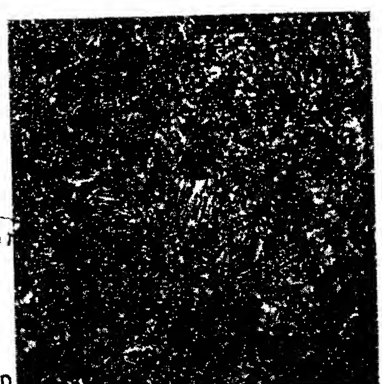
(*b*) Ferrite and Pearlite ×100.

(*c*) Pearlite ×250.

(*d*) Martensite ×250.



(*e*) Troosite and Martensite ×250.



(*f*) Sorbite ×250.

Fig. 17.

Other structures that may be found in iron-carbon alloys when the rate of cooling is sufficiently rapid or, in some cases, when other elements are present, are *sorbite*, *troosite*, *martensite*, and *austenite*. These are shown in Fig. 17.

Sorbite. This, like pearlite, is a mixture of ferrite and cementite, but, whereas in pearlite the two constituents are in layers, in sorbite they are in small particles all intermingled and having no regular pattern. A sorbitic structure gives ductility combined with toughness and strength, although the ductility will be less than that of a mild steel.

Martensite. This is obtained when a steel having a fairly high percentage of carbon is cooled rapidly from certain temperatures. It is seen under high magnifications (×1,000) as a structure consisting of a criss-cross medley of needle-like crystals. A martensitic structure gives the greatest hardness and strength obtainable in any iron-carbon alloy ; the ductility will, however, be almost zero and the impact strength very low.

Troosite. This is obtained by a slightly lower rate of cooling than will give a purely martensitic structure and, under high magnification, it appears as a light background in which are embedded black, somewhat rounded, grains. The light background is martensite. The nature of the black grains is not known exactly. Troosite is very hard and its presence makes machining very difficult.

Austenite. This is a solid solution of iron-carbide in iron and is not normally found in a carbon-iron alloy at ordinary temperatures. At high temperatures iron-carbon alloys are wholly austenitic, all the carbon going into solution ; on cooling at ordinary rates the carbon comes out of solution and the structure consists of the other constituents described above. By extremely rapid cooling, such as would be given by quenching a very small mass in ice-cold water, the austenitic structure might be retained at ordinary temperatures ; it can also be retained, with much slower rates of cooling, by adding certain elements such as manganese and nickel in fairly large percentages. Austenite is non-magnetic.

As has been mentioned above, free carbon may occur in the structure ; this carbon may be present as small particles more or less uniformly distributed, as large nodules or as definite flakes between the pearlite and ferrite grains. Ordinary cast iron generally contains graphite flakes and it is these that make this material weak in tension. By various means, some of which are considered later, the graphite may be largely dispersed and the strength of the cast iron be thereby increased.

Whether the structure of an iron-carbon alloy will consist of ferrite, pearlite, etc., depends not only on the percentage of carbon but also on the heat treatment the metal is given ; it may, to some extent, be determined by means of a diagram which is called the *constitutional* or *equilibrium diagram* for the alloy. This diagram is built up from the results

of numerous " cooling down " experiments made on the alloys and these experiments will now be considered.

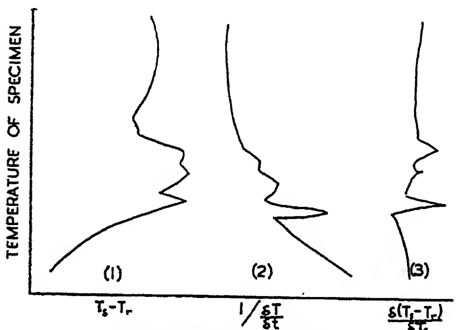
Cooling Curves. If a piece of steel containing 0·45 per cent of carbon is heated to a temperature above 1,500° C. it will be wholly liquid. On being allowed to cool naturally the temperature will fall steadily until it reaches about 1,500° C. at which temperature the mass will commence to solidify. During solidification the temperature will fall steadily until, when a temperature of about 1,130° C. is reached the mass will be wholly solid. Between 1,500° and 1,130° C. there were solid particles of austenite in the remaining liquid, which consisted of iron with carbon in solution. After solidification the temperature will continue to fall steadily until it reaches about 780° C. when it will remain approximately steady for a time before beginning to fall once more. Such a halt in the steady change of temperature is called an *arrest* and denotes a change in the internal structure of the material ; in the example considered the change is one from a structure consisting wholly of austenite into one consisting of austenite and β-iron. After the arrest at 780° C. the temperature will again fall steadily down to about 768° C. when a second arrest will occur. This second arrest occurs with all alloys of iron and carbon provided the percentage of carbon is not greater than about 0·55 and denotes a change in the form of the iron from the β-form (which is non-magnetic) to the α-form (which is magnetic). After the second arrest the temperature again falls steadily down to about 695° C. when a third arrest occurs, denoting a change of all the remaining austenite into ferrite and pearlite; the temperature at which this change occurs is unaffected by the percentage of carbon in the alloy. After the third arrest the temperature will fall steadily to atmospheric.

If the piece of steel is now heated at a uniform rate, i.e. with constant input of heat per unit of time, similar arrests will occur, but usually at slightly higher temperatures than during cooling. The arrests that occur during cooling are denoted by the symbol *Ar*, *A* standing for *arrêt* and *r* for *refroidissement* or cooling ; while arrests that occur during heating are denoted by *Ac*, *c* being for *chauffage* or heating. The three arrests, in the order in which they occur during heating, are given suffixes 1, 2, and 3. Thus the arrests described above are denoted by Ar_3, 780° ; Ar_2, 768° ; and Ar_1, 695°. The arrest temperatures are of importance because the variations in the physical properties of metals brought about by heat treatment are due to changes of structure that occur at the arrest temperatures or to the suppression of those changes by means of rapid cooling or otherwise.

By using the *inverse rate* method of plotting the results of cooling experiments, devised by Osmond, the arrests can be made more noticeable on the resulting graph. Let t_1, t_2, etc., be the successive times for rises or falls of x degrees, x being a constant quantity, and

let T_1, T_2, etc., be the actual temperatures of the specimen at the middle points of the time intervals; then the inverse rate curve is obtained by plotting the temperatures T_1, etc., as ordinates, against the times t_1, etc., as abscissæ. This is, approximately, equivalent to plotting the temperatures T against the quantity $1\Big/\frac{dT}{dt}$, hence the name *inverse rate* curve.

A more commonly used method of obtaining cooling curves is to use three thermo-couples, two in the specimen and one in a standard body, such as a lump of platinum, that has no arrests; the couple in the standard body is connected in series with one of the couples in the specimen so that the difference, ϕ, between the temperatures of the standard body and the specimen can be recorded, while the second couple in the specimen records the actual temperature T of the specimen at any instant. Then ϕ is plotted as abscissa against T as ordinate.



(1) DIFFERENTIAL CURVE.
(2) INVERSE RATE CURVE.
(3) DERIVED DIFFERENTIAL CURVE.

FIG. 18.

Yet another method of plotting is to plot the change in the difference ϕ during equal increments or decrements of T. This is equivalent to plotting $d\phi/dt$ and gives what is called the *derived differential* curve. The three types of curve are shown in Fig. 18. For a full consideration of the methods of conducting cooling experiments and of plotting the results the reader is referred to a paper by W. Rosenhain in *Proc. Physical Society*, Vol. 21.

Equilibrium Diagrams. When the arrest points for a large number of iron-carbon alloys containing different percentages of carbon have been determined, they may all be plotted on one diagram thus giving the *iron-carbon equilibrium* or *constitutional diagram*. It is shown, somewhat simplified, in Fig. 19.

At temperatures above those indicated by the line ABC the alloy, whatever its carbon content, will be wholly liquid; the line ABC is therefore called the *liquidus*. At temperatures below those indicated by the line ADBJ the alloy will be wholly solid; the line ADBJ is therefore called the *solidus*. The lines EGD, IGK, and HF indicate the temperatures at which certain changes occur in the solid mass of the alloy; for example, a constituent which is soluble at a moderately high temperature

may be insoluble at lower temperatures and so if the temperature is gradually reduced that constituent will have to be precipitated out of solution and this will occur although the mass is solid all the time. If the temperature is increased again then the constituent will again go into solution.

Consider what happens when a carbon-iron alloy containing 3 per cent of carbon is cooled slowly from the liquid state. At the temperature corresponding to the point X the alloy is a homogeneous solution of

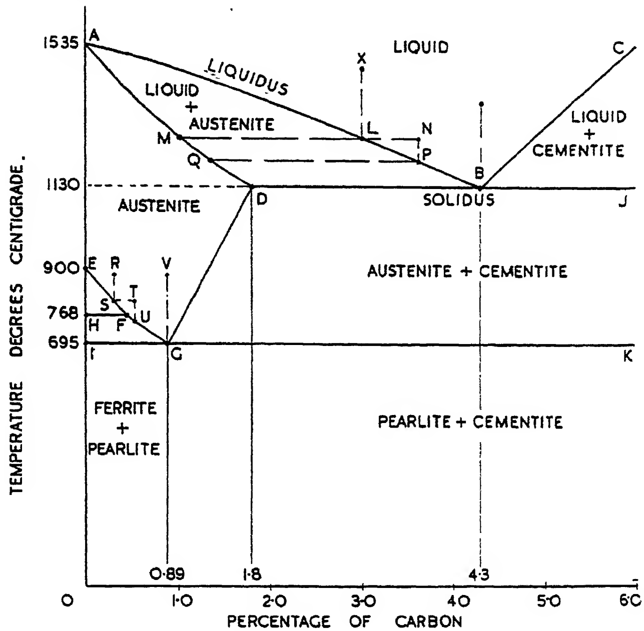


FIG. 19.

carbon in iron. When the temperature falls to that corresponding to the point L particles of solid matter begin to settle out. These particles will be composed of austenite and will have a composition as indicated by the point M on the solidus AD, the line LM being drawn horizontal. The austenite particles that are the first to settle out thus contain, in the example, about 1·1 per cent of carbon, that is, considerably less than the average (3 per cent) for the whole mass. It follows that the liquid that remains contains a slightly higher percentage of carbon than the average for the whole mass. The condition of the remaining liquid will, therefore, be represented by some point such as N, and the temperature will have to fall to that corresponding to the point P before further solidification occurs. The particles that then settle out will have a composition as indicated by the point Q. Actually the process will be a continuous

one and will not occur in steps as described. The solid particles that settle out will have compositions ranging from that corresponding to the point M to that corresponding to the point D while the composition of the remaining liquid will be indicated by points on the curve LB. When the liquid comes to have a composition corresponding to the point B it will freeze throughout at the temperature corresponding to B, i.e. at 1,130° C. The solid particles that separated out with the composition M had less carbon than those that separated out later on, those with the composition D being richest in carbon. If the cooling is fairly slow, however, the particles weak in carbon may absorb more carbon from those strong in carbon, and from the surrounding liquid, and the variation in carbon content would be reduced. Finally, all the solid particles might come to have the composition D and the structure immediately after solidification would then be a quantity of particles of composition D embedded in a matrix of composition B. Usually the cooling is not slow enough for such uniformity of composition to be attained.

Eutectic Alloys. An alloy containing 4·3 per cent of carbon will remain liquid until the temperature corresponding to B (1,130° C.) if reached and will then freeze throughout at that temperature. This is characteristic of certain alloys and these are called *eutectic alloys* or, shortly, *eutectics*. The eutectic alloy has the lowest freezing temperature of any of the alloys that can be formed from its constituents and in structure is an intimate mixture of two constituents. Thus in the case under consideration the structure of the eutectic alloy immediately after solidification will be an intimate mixture of austenite and cementite.

Eutectoids. Now consider what will happen to an alloy whose state is represented by the point R and which is cooled slowly. When the temperature corresponding to S is reached the mass, which is, of course, completely solid, will begin to deposit pure iron,[1] i.e. ferrite. The remaining alloy (austenite) will consequently be slightly richer in carbon and its state will be represented by some point such as T. The temperature will, therefore, have to fall to that corresponding to U before more ferrite is deposited. Again the process will be a continuous one, ferrite being deposited out and the composition of the remaining alloy changing as indicated by points on the line SG, until the composition G is reached; the remaining austenite will then change, all at once, to a mixture of ferrite and cementite in the form of a layered structure. This structure is known as pearlite. If the original alloy had been represented by the point V no ferrite would have been deposited until the temperature reached 695° C. and then the ferrite and cementite would be deposited in the form of pearlite. This particular composition thus exhibits a similarity to the eutectic alloy and it is consequently called the *eutectoid* alloy.

[1] Actually the ferrite will contain a little carbon in solution but with the simplified diagram assumed the description given applies.

If the austenite considered in the previous paragraph had contained more than 0·89 per cent of carbon then, on cooling, cementite would have been deposited and the remaining austenite would have become progressively weaker in carbon (the point representing its composition moving down the line DG) until finally pearlite would have been deposited at the point G.

An alloy containing more than 4·3 per cent of carbon will (when cooling down from the molten state) begin to deposit particles of cementite and the state point will move down the branch CB of the liquidus until finally the eutectic alloy solidifies at 1,130° C.

The Effects of Rapid Cooling. Unless the rate of cooling is quite low there may not be time for the actions described above to take place or, at any rate, to be completed, and the final structure will be different from what it would have been had there been sufficient time for the changes to occur fully. With extremely rapid cooling, such as would be produced by quenching small pieces of steel in ice-cold water, all the changes might be suppressed and the austenitic structure retained. With the most rapid rate of cooling used in practice a martensitic structure will be produced in medium and high carbon steels. Slightly slower cooling gives troosite and still slower cooling sorbite. The hardness of the martensitic structure is the greatest attainable in steel, troosite and sorbite being much softer. The presence of troosite, however, may make machining, by any process other than grinding, impossible.

The Heat Treatment of Steels. Broadly speaking this phrase covers the processes by which the required structures, and consequent physical properties, are obtained in the steel by heating it to suitable temperatures and then cooling it at suitable rates. The chief treatments are:

1. Annealing.
2. Normalising.
3. Hardening.
4. Tempering.
5. Stress relieving.
6. Carburising, nitriding, and other processes for producing surface hardness. These are considered later on.

Annealing. This consists in slowly heating the steel to a temperature somewhat above that defined by the line EGK in Fig. 19, for the given carbon content, and then letting it cool down in the furnace or at a very slow rate. The objects sought are threefold: first, to relieve any internal stresses remaining in the metal as the result of previous treatment; secondly, to soften the steel by producing a pearlitic structure; and thirdly, to bring the steel to a condition suitable for subsequent heat treatment.

Normalising. This is done by heating the steel to temperatures somewhat above those defined by the line EGD (Fig. 19) and letting it

cool in air. It produces a homogeneous structure consisting either of finely laminated pearlite or sorbite ; it also reduces the size of the crystal grains which may have been increased by prolonged heating during earlier processes. A normalised steel is usually stronger and harder, and may be more machinable than an annealed steel.

Hardening. This is done by heating the steel to temperatures equal to those used, for the same carbon content, in annealing and then quenching it in water or oil or, sometimes, in other substances. Usually a martensitic structure is desired as the result of hardening and with plain carbon steels this requires very rapid cooling. The addition of certain elements enables the cooling rate to be much lower and this is one of the most important advantages of the alloy steels, the less drastic quenching required obviating distortion and cracking difficulties.

Tempering. This consists of heating a hardened steel to a temperature somewhere between atmospheric and about 695° C. and then cooling it fairly rapidly by quenching in water, oil or other fluid. The process relieves the severe internal stresses produced by the hardening process and partly breaks down the martensitic structure, thus making the steel less brittle though softer. Untempered hardened steel will scratch glass but is exceedingly brittle ; as the temperature at which the steel is subsequently tempered is raised, the steel becomes softer but tougher. In a recently developed process, called *austempering*, the steel is heated to a temperature above the critical temperature so as to render it austenitic and is then transferred to a salt bath held at a temperature between 150° and 450° C. for a time depending on the size of the article and the composition of the steel. Finally the article is cooled in air or water. The advantages of this process over ordinary hardening and tempering are : first, a saving in time, and secondly, an improvement in the impact strength, percentage elongation, and reduction of area for a given hardness value.

Stress Relieving. In this treatment articles are heated to temperatures which while high enough to enable internal stresses set up by previous processes, either mechanical or thermal, to be relieved, is not high enough to produce any change in the structure of the material.

Plain Carbon Steels. Plain carbon steels are still the most widely used of any steels despite the great increase in the use of alloy steels. The effect of varying the percentage of carbon on the physical properties is shown by the following table :

Carbon Per cent	*Annealing temp. ° C.*	*Ultimate strength Tons per sq. in.*	*Elongation Per cent*	*Brinell No.*
0·2	900	26–30	35–20	111–126
0·3	890	29–34	28–18	121–149
0·4	860	35–40	20–15	159–179
0·6	840	45–50	—	196–225
0·75	810	50–55	—	225–255

The effect of tempering at different temperatures after hardening is shown in Fig. 20.

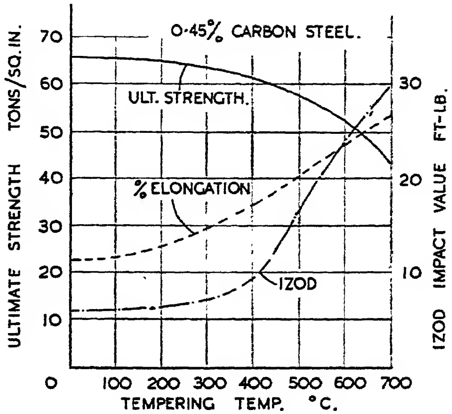


FIG. 20.

When the carbon content exceeds about 0·45 per cent. the steel is inclined to be brittle even in the annealed condition, and such steels are not used for structural parts or machine components.

As previously stated, plain carbon steels are widely used, being cheap and having properties that make them quite suitable for a wide range of purposes. When the necessary physical properties cannot be obtained in a plain carbon steel then an alloy steel must be used; these are considered later.

Mass Effect. The rate at which an article undergoing heat treatment can be cooled depends on its size and mass, small articles of thin section being obviously easier to cool quickly than large, thick ones. The differences in the mechanical properties due to variation in size are shown in Fig. 21, from which it will be seen that this mass-effect is much more marked in plain carbon steel than in the alloy steels and that in the plain nickel steel the Izod impact test value is adversely affected as the size increases. One of the objects sought in using various alloying elements is the reduction of this mass-effect.

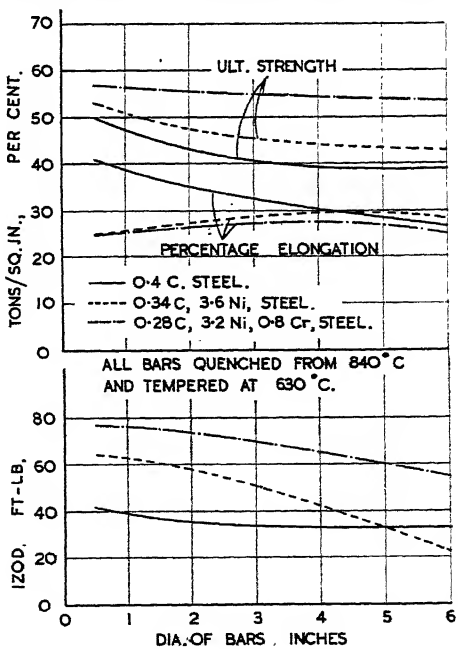


FIG. 21.

Alloy Steels. An alloy steel is one in which elements, other than carbon

and iron, are present in sufficient quantities to modify the properties of the material. The chief alloying elements are manganese, nickel, chromium, molybdenum, silicon, vanadium, tungsten, cobalt, and copper. In general these elements have two effects on the steel containing them. These are: (1) *Indirect effects*, and (2) *Direct effects*. The indirect effects are a raising or lowering of the temperatures at which the transformations from one type of structure to another occurs, or an alteration in the critical cooling rate that will give a certain structure. Thus manganese, chromium, molybdenum, vanadium, and tungsten all facilitate the production of carbides by combining with the carbon present, but nickel and silicon do not themselves form carbides and tend to decompose iron carbide.

The direct effects are illustrated by the reduction in grain size produced by nickel, the resistance to corrosion and oxidation brought about by chromium and the stability under high temperature conditions conferred by tungsten and molybdenum.

The number of alloy steels available to the engineer is now so great that it is impossible in a book of this character to deal, even briefly, with all of them; only the most important groups can be mentioned. The costs of alloy steels vary widely; some are only a little more expensive than plain carbon steels, others are ten to twenty times as costly. Some alloy steels require very carefully controlled heat treatments, others are easier to deal with in this respect. Thus alloy steels are used only when the necessary properties cannot be obtained in a plain carbon steel, for example, where very high mechanical properties or great resistance to corrosion are required or where high temperatures have to be withstood. The most important groups of alloy steels are:

1. Manganese steels.
2. Nickel steels.
3. Nickel-chrome, nickel-chrome-molybdenum, and nickel-chrome-vanadium steels.
4. Stainless steels.
5. Silicon steels.
6. Tool steels and steels for magnets.

Manganese Steels. All steels contain small amounts of manganese, this element being used to bring about deoxidation of the molten steel during manufacture and to mitigate the bad effects of any sulphur present. Manganese combines with sulphur and prevents or reduces the formation of iron sulphide which renders steel "red short," that is, brittle at forging temperatures. According to F. G. Norris,[1] the value of the ratio $\frac{\text{Mn}+0{\cdot}048}{\text{S}+0{\cdot}130}$ is the important factor; if that ratio is greater than 6·63 steel will never be red short, if the ratio is less than 3·30 steel will always be red short, while for intermediate values the heat treatment

[1] "Factors Affecting Red Shortness." *Journal Iron and Steel Inst.*, Vol. 138, 1938.

will determine whether the steel will be red short or not. Manganese also improves the rolling qualities of steel and a small excess, up to about 0·35 per cent, is generally provided beyond that necessary to ensure proper deoxidation. The true manganese steels contain larger amounts and fall into two groups :

(*a*) Those containing from 1 to 2 per cent of manganese ;
(*b*) Those containing from 11 to 14 per cent.

The steels in group (*b*) contain from 1·0 to 1·3 per cent of carbon and before heat treatment are very hard and possess no ductility ; when heated to about 1,050° C. and quenched rapidly they become tough and comparatively soft but are rapidly hardened by cold working and then develop very great resistance to wear. This work hardening property makes machining very difficult and necessitates the use of tools which are kept very sharp, but it makes the steels eminently suitable for railway and tramway points, dredger buckets, stone-crusher parts, etc., which are subject to severe conditions as regards wear.

The steels in group (*a*) contain only from 0·25 to 0·55 per cent of carbon and exhibit similar properties to the steels of group (*b*) but to a much smaller degree. In recent years low carbon, low manganese steels have been greatly developed and are being used by a number of motor-car manufacturers, particularly in America, instead of the more expensive alloy steels. Mild steels containing about 1·5 per cent of manganese are also now being used for structural purposes ; for a given ductility they show a higher ultimate strength and better Izod figure than carbon steels.

Nickel Steels. The plain nickel steels are widely used and may be divided into four groups :

(*a*) Steels containing up to 6 per cent of nickel ;
(*b*) Steels containing 20–30 per cent of nickel ;
(*c*) Steels containing 30–40 per cent of nickel ;
(*d*) Steels containing 50 per cent or more nickel.

The group (*a*) steels are used for parts of machines and structures that are highly stressed ; they contain 0·1–0·55 per cent of carbon, 0·3–0·8 per cent manganese, and 0·4–6 per cent of nickel. The steels of this group containing low percentages of carbon (0·1–0·25) are used for case-hardening and are dealt with later.

Nickel tends to produce graphitisation of the iron-carbide in steel and the manganese content is required partly to counteract this action and partly for the normal purpose of deoxidising the steel. Nickel helps to prevent excessive grain growth at high temperatures and thus enables fine grain steels to be produced more easily ; it also lowers the critical temperatures slightly and thus makes heat treatment a little less severe. The principal attributes of the nickel steels are thus great strength together with considerable ductility and toughness. This is brought out

by the curves given in Fig. 22, which show the properties of a 1 per cent and a $3\frac{1}{2}$ per cent nickel steel after hardening by quenching in oil from 850° C. and tempering at various temperatures up to 700° C.

Steels containing about 0·4–0·5 per cent of carbon and from 20 to 30 per cent nickel are austenitic in structure even when cooled slowly and, besides being extremely tough, are highly resistant to corrosion by sea-water, steam, and hot gases. They also have low coefficients of thermal expansion and are used for steam turbine blades, internal combustion engine valves, etc. They are non-magnetic, a property of which

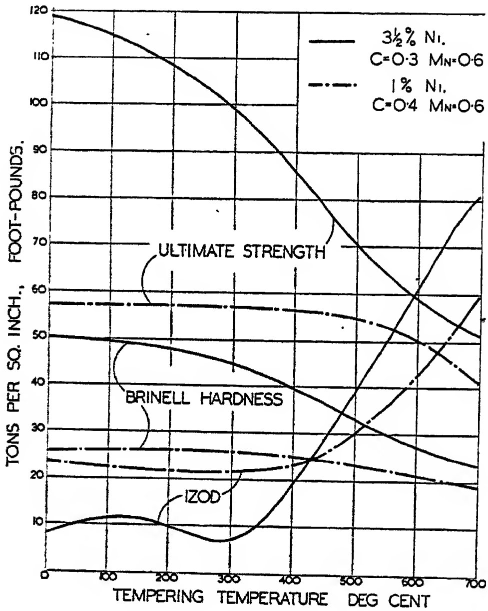


Fig. 22.

use is made, and always contain about 1·4 per cent manganese and 0·5 per cent of chromium. The only heat treatment they are given is heating to about 800° C. and cooling in air to render them machinable.

The steels in group (*c*), containing 30–40 per cent of nickel, possess very low coefficients of thermal expansion and are used for measuring-rods and other applications where this property is required.

The steels in group (*d*) possess the property of high magnetic permeability.

Nickel-Chrome Steels. These are probably the most widely used of all alloy steels. The compositions mainly used are: carbon, 0·1–0·55; nickel, 1·0–4·75; chromium, 0·45–1·75; manganese, 0·3–0·8. The steels containing up to 0·35 per cent of carbon are used for case-hardening

and the others for general purposes where high mechanical properties are required. In Fig. 23 are shown the properties of a steel having the composition carbon 0·3, nickel 3·4, chromium 0·75 after hardening by quenching in oil from 830° C. and tempering at various temperatures. The dip in the Izod curve that occurs when the tempering temperature is between 250° and 450° C. should be noted; it is typical of these steels and those temperatures must not be used for tempering. The steels must also be cooled fairly rapidly from the tempering temperature or the impact test figure will be very low; this marked reduction in the impact strength when the cooling is slow is called *temper brittleness* and is indicated by the dotted line in Fig. 23.

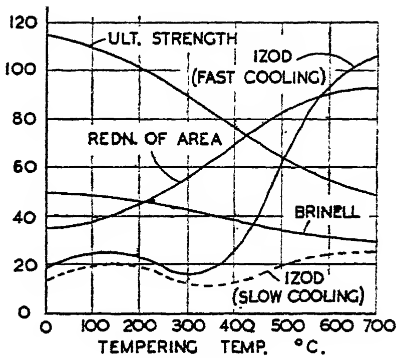


FIG. 23.

When the chromium content is over 1 per cent and the nickel content over 4 per cent the steel may be hardened by cooling in *air* from a temperature above the critical temperature. Such steels are called *air-hardening steels*; they possess outstanding properties and are used for heavily loaded toothed gears and machine parts.

Nickel-Chrome-Molybdenum Steels. The temper brittleness of the nickel-chrome steels is eliminated (but the dip in the Izod curve remains) by the introduction of 0·3–0·6 per cent of molybdenum and this addition also makes the mass effect much less pronounced, so that large pieces can be more easily heat treated. This property of molybdenum is very valuable because it enables large forgings to be cooled slowly from the tempering temperature; they can therefore be straightened while at the tempering temperature and the stresses set up by the straightening are subsequently relieved during the slow cooling of the forging.

The addition of molybdenum to a nickel-chrome steel also enables an increased percentage of manganese to be used without producing any reduction of impact strength, while the increase in the manganese enables the nickel content to be reduced and thus makes the steel cheaper. Thus a steel having the composition, carbon 0·35, manganese 1·6, nickel 2·0, molybdenum 0·6, will have properties almost identical with one whose composition is carbon 0·35, manganese 0·6, nickel 3·0, chromium 0·8.

In most respects the nickel-chrome-molybdenum steels are similar to the nickel-chrome steels and they are used for similar purposes; a famous example is the *Kayser Ellison* " K.E. 805 " which has the composition, carbon 0·35, silicon 0·35, manganese 0·4, nickel 1·25, and molybdenum 0·3.

A steel containing from 0·25 to 0·75 per cent molybdenum as the sole alloying element (in addition to carbon and a small amount of manganese) is used for structural purposes. Like the silicon structural steel mentioned later on it gives a greater strength for a given ductility than a plain carbon steel gives.

Nickel-Chrome-Vanadium Steels. Vanadium is never used as the sole alloying element in steels but in conjunction with nickel and/or chromium. It is a very effective deoxidising element and thus, by eliminating or greatly reducing the iron oxide content of steel, it improves the mechanical properties generally and the fatigue strength in particular; it also intensifies the effect of other elements and enables somewhat smaller contents of those elements to be used without alteration of the physical properties of the steel. Its direct effect is to harden steel and it is not normally used in excess of about 0·2 per cent except in tool steels.

Stainless Steels. There are several fairly distinct types of stainless steel but they all contain fairly large percentages of chromium and sometimes of nickel. The chromium ranges from 4 to 22 per cent and the nickel from 0 to 26 per cent. The stainless steels are sometimes grouped into four groups, namely: (1) *Martensitic*, chromium 10–14 per cent; (2) *Ferritic*, chromium 14–18 or 23–30 per cent; (3) *Austenitic*, chromium 15–20, nickel 10–7 per cent; (4) *High austenitic*, chromium 22–26, nickel 12–14 per cent. Probably the most important group is that containing 15–20 per cent chromium and 10–7 per cent nickel; a steel containing 18 per cent chromium and 8 per cent nickel is very widely used and is commonly referred to as 18/8 steel. The steels in the 18/8 group are austenitic in structure even when cooled slowly and they are not amenable to heat treatment, except that they can be annealed by quenching from 1,100° C. and are then very tough and ductile. They are hardened by cold-work, the tensile strength being increased and the ductility decreased. In the annealed state the following mechanical properties can be obtained:

Ultimate strength	35–55 tons per sq. in.
Elongation	50–70 per cent
Izod figure	80–100 ft.-lb.

These properties are maintained fairly well at moderately high temperatures while the impact strength is maintained at very low temperatures, this being somewhat exceptional. These steels have excellent corrosion-resisting properties but they are liable to inter-crystalline corrosion after being heated to between 600° and 900° C. This must be borne in mind when the steels are welded; the trouble can be obviated by quenching the steel from about 1,050° C. The steels can be manipulated by all the usual processes and machine quite well provided the tools used are kept sharp.

If the maximum ductility is required the carbon content of these steels must be kept low.

For cutlery and general engineering purposes stainless steels commonly contain no nickel, the chromium content is 12–14 per cent, and the carbon 0·3–0·55 per cent. These steels are amenable to heat treatment and may be hardened by quenching from about 950° C., in oil for medium sections and in air for light sections. For cutlery the carbon is kept below 0·35 per cent and tempering is done at about 250° C. ; for general engineering purposes the higher carbon contents are used and tempering is done between 600° and 700° C., which gives the following properties :

Ultimate strength	60–70 tons per sq. in.
Elongation	15–20 per cent
Izod value	15–25 ft.-lb.
Brinell hardness	220–320

The heat-resisting properties of this group are increased by the addition of about 3 per cent of silicon.

When the carbon content is below 0·15 per cent the alloys are called stainless irons.

Silicon Steels. Small amounts of silicon are frequently used in many alloy steels but the percentage does not usually exceed about 0·8. Mention has, however, just been made of the use of up to 3 per cent in heat-resisting stainless steels. A silicon content of 1·25–2·5 per cent (with 0·5–0·65 per cent carbon and 0·6–0·9 per cent manganese) is frequently used in steel for springs, such steel having a high fatigue strength ; the springs are quenched in oil from between 857° and 900° C. and are tempered between 475° and 525° C.

Steel containing from 0·5 to 1 per cent of silicon and 0·7–0·95 per cent of manganese is now being used for structural purposes. These steels, like the molybdenum steel previously mentioned, give a greater strength and higher ductility than plain carbon steels.

An *iron* containing less than 0·05 per cent carbon, about 0·3 per cent manganese, and 3·4 per cent silicon possesses extremely low magnetic hysteresis and is widely used for the laminations of electrical machines ; this valuable property is much reduced by cold-work and this should be avoided so far as is possible.

The table on pp. 47–49, gives brief particulars of a number of British Standard steels. The report from which this table is extracted is well worth study.

Tool Steels. Plain carbon steels containing from 0·8 to 1·3 per cent of carbon were at one time the only tool steels available, but their use is now very much restricted. The addition of 1–2 per cent of manganese to these steels reduces the dimensional changes that occur during hardening, which is done by quenching in oil from about 800° C. ; tempering

is done at about 200° C. These steels are used for press tools and applications where the conditions are not severe. The cutting tool steels mostly used nowadays are the *high-speed steels*; of these there are numerous varieties and the table below gives a number of typical compositions. Roughly these fall into five groups, namely,

1. The 18–4–2 group containing about 18 per cent of tungsten, 4 per cent of chromium, and 1–2 per cent of vanadium.
2. The 18–4–2 low cobalt group, similar to 1, but containing 4–6 per cent of cobalt.
3. The 18–4–2 high cobalt group, similar to 1, but containing 10–18 per cent of cobalt.
4. The high chromium group containing about 14 per cent chromium.
5. The molybdenum group.

Molybdenum	*Carbon*	*Manganese*	*Silicon*	*Tungsten*	*Chromium*	*Cobalt*	*Vanadium*
—	0·78	0·3	0·25	18·5	4·2	—	1·1
—	0·79	0·3	0·25	19·0	4·5	4–6	1·4
—	0·79	0·3	0·25	19·0	4·5	10–18	1·4
—	1·23	0·39	0·37	3·2	14·1	—	—
—	1·61	0·23	0·43	—	13·7	—	—
8·5	0·75	0·3	0·25	2·5	4·2	0–5	1·0
8·5	1·2	0·37	0·35	2·5	—	—	1·75–2·5

Tungsten steels containing smaller percentages of tungsten (up to 10 per cent) are used for cutting tools, for less severe duties than those given above, and also for wire drawing dies.

High-speed steels require slow heating in the early stages, otherwise cracking will occur, but they must be heated rapidly through the range 600°–800° C. They are hardened by " quenching " from a temperature ranging from 1,250° to 1,400° C., usually in dry air but sometimes in oil or even in molten lead. Their hardness is *increased* by a second heating to between 550° and 600° C., being then about 700 Brinell; heating to 800° C. will reduce the hardness to about 300 Brinell. Thus high-speed steels are not exceptionally hard, in fact a plain carbon steel can easily be made to give a greater hardness; but whereas the hardness of a plain carbon steel will fall off at temperatures greater than about 250°–300° C. the high-speed steels retain their hardness up to about 600° C. The structure of a high-speed steel after hardening is usually a mixture of martensite and troosite with tungsten and cobalt carbides distributed throughout the mass.

The phenomena associated with the hardening of high-speed tool steels are very complex. E. G. Herbert and others have found that after hardening, followed by secondary heat treatment, the hardness varies in a cyclical manner for considerable periods. During this cyclical variation the hardness can be stabilised at a high or a low level by means of a magnetic treatment given at a moment when the cyclical hardness is at a maximum or a minimum as the case may be. A low temperature treatment (at about 100° C.) subsequent to stabilising has also been found

beneficial. Improvements in the life of twist drills following these treatments have been found to range up to as much as 120 per cent. Cyclical variations in the hardness can also be started at any time, subsequent to hardening, by suitable thermal or magnetic treatment. For information on this matter the reader is referred to Herbert's paper, *Proc. I. Mech. E.*, April, 1933.

The S.A.E. Specification System. The Society of Automotive Engineers, of America, has standardised a range of steels suitable for various purposes and has designated these steels by numbers which serve, to some extent, to indicate their compositions. The first numeral represents the class of the steel according to the following grouping:

Carbon steels	1	Chromium steels	5
Nickel steels	2	Chrome-vanadium steels	6
Nickel-chrome steels	3	Tungsten steels	7
Molybdenum steels	4	Silico-manganese steels	9

In the alloy steels, the second numeral (and third, if necessary) indicates the percentage of the principal alloying element. The last numerals give the percentage of carbon multiplied by 100. Thus S.A.E. 2340 indicates a 3 per cent nickel steel containing 0·4 per cent of carbon. S.A.E. 71360 indicates a steel containing 13 per cent of tungsten and 0·6 per cent of carbon.

Carbide Cutting Materials. High-speed steels have, to a large extent, been replaced by cutting materials which are not steel at all but are composed essentially of particles of the carbides of tungsten, cobalt, titanium, and tantalum held in a matrix of cobalt or nickel. These materials are known as *cemented carbides.* Tungsten and cobalt carbides are the most widely used and tungsten carbide is always the chief constituent; the addition of titanium and tantalum carbides is made in order to eliminate a form of wear that occurs when a plain tungsten carbide material is used to cut steel. The addition, however, reduces the strength of the material. Since the impact strength of the cemented carbides is low and their cost is high they are invariably used as tips brazed on to tool steel shanks. The manufacture of the carbides is a difficult process which cannot be here considered, but it should be noted that by varying the manufacturing process different varieties of material can be obtained; some of these are comparatively tough but not of maximum hardness, others are extremely hard but lacking in impact strength, while, as has been mentioned, some materials possess peculiar properties as regards the abrasion produced by the rubbing of steel chips on them. The hardness of these carbide materials ranges from 70 to 85 on the Rockwell C scale; it falls off slowly as the temperature rises but at 800° C. it is still greater than that of high-speed steel at room temperatures.

Magnet Steels. Many materials have been developed for use as permanent magnets and the magnetic properties have been improved enormously in the last two decades. A steel containing 5–10 per cent of cobalt and 0·9 per cent of carbon has been much used, but steels having compositions 30–40 per cent cobalt, 0·4–0·8 per cent carbon, 1·5–3 per cent chromium, and 5–9 per cent tungsten possess improved magnetic properties. Steels containing high percentages of nickel and aluminium possess even better properties, an example of such a steel being *Alnico* which contains 20 per cent of nickel, 10 per cent aluminium, and 10 per cent cobalt. Steels containing 10–25 per cent nickel, 15–36 per cent cobalt, and 8–25 per cent titanium are now coming into use.

Miscellaneous Steels. A steel containing 0·5 per cent of chromium, 1·25 per cent manganese, 0·8 per cent silicon, and 0·2–0·45 per cent carbon is coming into use for structural purposes; with 0·2 per cent carbon it gives a maximum stress of about 40 tons per sq. in. and with 0·45 per cent carbon this is raised to about 65 tons per sq. in. A molybdenum steel containing 0·2–0·7 per cent carbon and 0·15–0·25 per cent molybdenum as the sole alloying elements has recently come into use. This steel, which goes by the trade name of *Amola*, is remarkable in that its grain size can be controlled very accurately; it is made in four standard grain sizes ranging from a grain that is only just a little finer than that of an ordinary fine-grained steel to one that is so fine as to be almost structureless. Steels containing from 0·05 to 0·45 per cent carbon and up to 0·3 per cent sulphur have for a long time been used for lightly loaded parts such as bolts, set-screws, pins, etc.; they machine very readily and with a good finish and are known as *free-cutting* steels. A later development in such steels is the use of up to 0·2 per cent of lead instead of sulphur. The lead is merely mixed with the steel and does not alloy with it; it gives a free-cutting steel but does not reduce the physical properties of the steel to the extent that sulphur does.

A material which goes by the trade name of *Inconel* is coming into extensive use because of its very high resistance to corrosion and oxidation even at high temperatures. Its composition is approximately 80 per cent nickel, 13 per cent chromium, and 7 per cent iron, so that perhaps it should be regarded as a non-ferrous material; it can be cast, forged, rolled, and cold drawn. It is not amenable to heat treatment except that it can be annealed by heating to about 1,000° C. Its tensile strength is, however, improved by cold-work and by forging, as will be seen from the table below.

Condition	*Ultimate strength Tons per sq. in.*	*Elongation Per cent (2 in.)*	*Brinell No.*	*Izod*
Castings	28–32	15–10	160	—
Forgings	36–42	50–30	130–170	120
Cold-drawn	70–80	10–2	—	—
Cold-drawn and annealed .	36–47	50–30	—	—

Inconel can be forged readily at temperatures between 1,000° and 1,300° C. but between 650° and 900° C. it is brittle.

Another nickel-chromium alloy, developed by Rolls Royce, Ltd., for the exhaust valves of aero engines, has the composition, carbon 0·09, silicon 0·65, manganese 1·24, nickel 77·7, chromium 18·7, and iron 1·1. It is air cooled from a temperature of 1,050° C.

Surface Hardening. When a part has to withstand conditions tending to produce wear on its surface and at the same time has to possess considerable strength to withstand the forces acting on it, it is commonly made of a tough material and is given a hard surface by one of several available methods. The principal methods are:

1. Carburising or case-hardening.
2. Cyaniding.
3. Nitriding.
4. Flame hardening.
5. The Tocco process.

1. Carburising. The part is made in a plain carbon or alloy steel with a carbon content of not more than 0·25 per cent and a surface layer with a carbon content of about 0·9 per cent is produced by packing the part (after machining to within a few thousands of the finished size) in a carburising material contained in a cast-iron box, heating to between 900° and 950° C. and maintaining it at that temperature for several hours; the time depends on the thickness of case required, the carburising material used, and on the actual temperature. The latter must be high enough to bring the iron of the steel into the γ-form, this being the only form that readily absorbs carbon; it must therefore be above the temperature given by the line EG in the equilibrium diagram on p. 29, for the composition of the steel. The carburising boxes must be provided with lids and it is important that these should be made gas-tight by luting with clay. Usually several articles are packed in the same box and some care must be taken to see that each article is completely surrounded by carburising material. The latter is essentially a material that is rich in carbon which it can give up to the steel; charcoal and mixtures of charcoal and barium carbonate and other substances are commonly used but the material is generally bought as a proprietary article. After the carburising operation is completed the article has a core with a carbon content up to 0·25 per cent. and a surface layer, usually from 1 to 2 mm. thick, having a content of 0·9–1·0 per cent of carbon. Cases thicker than about 2 mm. are not usually required or desirable since very thick cases lead to difficulties such as flanking and brittleness of the case. The article must now be heat treated so as to produce the maximum toughness in the core together with the maximum hardness of the case; for the best results a double treatment is generally required. The first is to refine the structure of the core which, as a result of the prolonged heating, is in a very coarse state, and the treatment is to heat the article

to a temperature just above that determined by the line GH (Fig. 19) *for the core composition* and then to quench it in water or oil. This treatment refines the core but leaves the case, and to some extent the core also, in a brittle condition; the second part of the treatment is designed to eliminate this brittleness and to produce a hard case and a tough core. It consists in heating the article to about 760° C. (that is, above the critical temperature for the *case* composition point G in Fig. 19) and again quenching in water or oil. The heating should be slow up to about 600° C. and then rapid up to 760° C. and so two furnaces are commonly used. Occasionally a third treatment may be given, namely, a tempering at between 150° and 200° C., chiefly to eliminate any thermal stresses set up by the previous treatments.

In order to reduce costs a single treatment only is often given, the part being quenched from a temperature about mid-way between those used in the double treatment; this does not give such good results as does the double treatment. Occasionally the articles are quenched immediately on being taken from the carburising boxes, but until recently this was definitely bad practice; because of the greater control over grain size now possible with modern steels it is now possible to get satisfactory results with direct quenching.

Nickel and nickel-chrome steels are widely used for case-hardened parts, the nickel, provided it is present to the extent of at least 3 per cent, producing a greatly increased toughness in the core; this is partly due to the action of nickel in preventing undue grain growth during the prolonged heating operation. The nickel content rarely exceeds 5 per cent. The addition of chromium produces a better wear-resisting case and makes the treatment of large parts easier; commonly used compositions are carbon 0·08–0·2, nickel 3–5, and chromium 0·25–1·5 per cent. Nickel-molybdenum steels with composition, carbon 0·15–0·25, nickel 1·5–2·0, and molybdenum 0·2–0·3 per cent are also used. Very good results can be obtained with these steels with a single heat treatment.

In recent years, and particularly for the continuous treatment of large numbers of articles, gases have come into extensive use as carburising agents. Natural gas (which is mostly methane, and which is available in the United States of America where the process has been chiefly developed) and propane (which is a waste product of the oil industry) are the commonly used gases. The articles to be carburised are placed in or travel through large muffle furnaces filled with the gases and heated either externally by direct heating or internally by radiant heat from internally heated refractory cylinders.

Cyaniding. This consists of immersing the article in a cyanide bath, maintained at 850°–950° C., for periods ranging from about 15 minutes up to 2–3 hours. At 950° C. a case 0·005 in. thick is obtained in about 5 minutes but, because of the fall in the temperature of the bath when a

batch of work is immersed in it, the actual time for a batch weighing, say, 50 lb. would be about 30 minutes, depending on the kind of furnace used. To get a case 0·030 in. thick in such a batch would require from $2\frac{1}{2}$ to 3 hours. The output can be greatly increased by pre-heating the articles in a separate bath or furnace. The salt used for the bath is a mixture of equal parts of sodium cyanide and sodium carbonate with small additions of barium chloride and calcium cyanamide. The cyanide content must be maintained between 50 and 60 per cent, for if it falls too low the penetration will be slow and if it rises too high decomposition and fuming will occur.

On removal from the bath the parts are quenched in water or oil and are then sometimes reheated to 760° C. and again quenched. By placing the articles in a second cyanide bath (held at a temperature of about 790° C.) before quenching, distortion troubles can be reduced. If the parts are in the bath for longer than about 2 hours then a refining treatment may have to be given to reduce the grain size. This is done after the first quench on removal from the bath and consists of heating the parts to about 900° C. and quenching in oil or water, the quench from 760° C. then following. By quenching in special salt solutions parts may be given blue, brown, or mottled appearances; quenching in aerated water gives a slightly brown, mottled appearance.

One advantage of the cyaniding process is that the bright finish of machined parts can, if required, be maintained; a second is that distortion is more easily avoided, partly because of the more even heating and partly because the parts can be suspended vertically in the bath; a third is that the change in hardness from the case to the core is more gradual and flaking of the case is eliminated. The hardness of the case is due partly to the absorption of nitrogen. Cyaniding is used chiefly for cases not exceeding $\frac{1}{32}$ in. in thickness, but special salt compositions are available which enable much thicker cases to be obtained if required. Because of the absence of scaling and the reduced distortion of cyanided parts the grinding allowance can be less than for work carburised in boxes.

Nitriding. This is done by putting the article in ammonia vapour at a temperature between 450° and 500° C. for periods up to 10 hours. No subsequent heat treatment is required and the core should be brought to its toughest condition, by quenching in oil from about 900° C. and tempering from about 600° C., before nitriding.

Certain steels react to this treatment much better than others and an aluminium content of about 1 per cent seems to be desirable. *Nitralloy* steels, which are covered by patents, and which were developed for the process, contain 0·38–0·43 per cent carbon, 0·2–0·3 per cent silicon, 0·4–0·6 per cent manganese, 1·6–1·8 per cent chromium, 0·15–0·25 per cent molybdenum, 0·3–0·6 per cent nickel, and 0·8–1·25 per cent

aluminium. The surface hardness is produced by the formation of very hard crystals of iron-nitride (Fe_2N) in the form of needles. The thickness of the case does not usually exceed about 0·8 mm. Some cast irons can be successfully nitrided; one suitable composition is carbon 2·6, silicon 2·6, manganese 0·61, chromium 1·7, and aluminium 1·4 per cent.

Flame Hardening. This process is sometimes referred to as the *Shorter* process, having been developed by Mr. A. E. Shorter. It consists of heating the surface to be hardened by means of an oxy-acetylene blow-pipe flame, and immediately quenching the heated surface by means of a spray or jet of water that is directed on to the surface. The water jet and blow-pipe are mounted together so that the water jet follows the blow-pipe at a distance of about an inch. The heating is very localised and distortion is reduced to a minimum; the process is therefore particularly useful for such articles as large gear-wheels which cannot be quenched as a whole and for the local hardening of portions of articles. The process can be carried out with quite simple apparatus, but to facilitate the operation and to enable consistent and reliable results to be economically obtained specially developed machines are generally used.

The Tocco Process. This process, which was developed for the hardening of the crank-pins and main bearing surfaces of motor-car crankshafts, consists of heating the surface to be hardened by means of a high-frequency electric current and then quenching by a spray of water. The high-frequency current is passed through a winding enclosed in a block of metal that encircles the pin being hardened; eddy currents are thereby induced in the metal near the surface of the pin and that metal is heated. The inner surface of the inductor block is grooved and, when the temperature of the pin has reached the proper value, water is circulated between the pin and the block. After hardening in this manner a low temperature treatment is given; the result is an extremely fine-grained Martensite having a Brinell hardness of about 600 at the surface, the hardness decreasing steadily as the core is approached. This gradual reduction in hardness makes the danger of the hardened skin "peeling" very slight. The process requires much less time than case-hardening and there is no scaling of the surface of the article; it requires special apparatus, however, and is not readily adaptable to a wide variety of articles, being essentially suitable for quantity production.

Local Hardening. When the carburising, cyaniding, and nitriding processes are used it is possible to harden certain selected portions of articles, leaving the remainder soft, by protecting the latter portions in some way so that they are not acted on by the carburising, cyaniding, or nitriding agent. This protection is usually done by copper plating the portions.

Cast iron. The term cast iron is used to describe a wide range of materials varying considerably in composition, but, roughly, cast iron

SOME BRITISH STANDARD STEELS

Technical Advisory Committee (T.A.C.) Ref. No.	*British Standard Specification En. No.*	*Type*	*Description*	*Condition*	*Maximum stress (M.S.) Tons per sq. in.*	*Elongation Per cent*	*Izod Ft.-lb.*	*Sizes*
1	1	Carbon	Free cutting steel (sulphur)	—	28 max. 25 min.	14 (cold finish) 26 (other finishes)	—	—
2A	—	”	Mild steel	Normalised	24–28	27	—	—
2B	2	”	”	”	26–32	28	—	—
3A	3	”	20–30 carbon steel	As rolled	25–35	25	—	—
3B	4	”		Normalised	25–35	25		All
3C	5	”		O.H. and T.	30–40	25	25*	
3D	2	”		Cold-drawn	25–35	17		
4	6	”	35–45 ton bright carbon steel	—	35–45	15	10–40	All
5	8	”	“ 40 ” carbon steel	Normalised	35–45	20	10–20	All
6A	9	”	“ 55 ” carbon steel	”	45 min.	18	—	All
6B	10	”	”	O.H. and T.	55 min.	15	—	—
7A	11A	C-Cr	“ 60 ” carbon-chromium	H. and T.	55–65	15	—	Up to 2½ in.
8A	12	Mn-Ni	40–50 ton carbon or alloy steel.	”	40 min.	22	35	All
8W	14	Car-Mn	40–50 ton alloy steel for welding.	”	40–55	20	35	Up to 4 in.
9A	16A, 17A	Mn-Mo	45–55 ton alloy steel	”	45	22	40	All
10A	16B, 17B	”	50–60 ton alloy steel	”	50 min.	20	40	4 in.
10E	24A	Ni-Cr-Mo	” ”	”	”	20	40	Over 4 in.
11A	16C, 17C	Mn-Mo	55–65 ton alloy steel	”	55 min.	18	40	2½ in.
11E	24B	Ni-Cr-Mo	” ”	”	”	18	40	Over 2½ in.
11G	25A	2½ per cent Ni-Cr-Mo	” ”	”	”	18	40	Over 4 in.
11X 11Y	20A	Ni-Cr-Mo Cr-Mo	55–65 ton alloy steel for bolts for service at steam temperatures.	”	55–65	17	40	—

* Up to 2½ in. only.

SOME BRITISH STANDARD STEELS—*continued*

Technical Advisory Committee (T.A.C.) Ref. No.	*British Standard Specification En. No.*	*Type*	*Description*	*Condition*	*Maximum stress (M.S.) Tons per sq. in.*	*Elongation Per cent*	*Izod Ft.-lb.*	*Sizes*
12A	16D, 17D	Mn-Mo	60–70 ton alloy steel	H. and T.	60 min.	17	35	1⅛ in.
12C	24C	1½ per cent Ni-Cr-Mo	” ”	”	”	17	35	2½ in.
12D	25B	2½ per cent Ni-Cr-Mo	” ”	”	”	17	35	Over 2½ in.
13A	24D	1½ per cent Ni-Cr-Mo	65–75 ton alloy steel	”	65 min.	16	35	2½ in.
13E	25C	2½ per cent Ni-Cr-Mo (Med. C.)	” ”	”	”	”	”	Over 2½ in.
14A	24E	1½ per cent Ni-Cr-Mo	70–80 ton alloy steel	”	70 min.	15	30	1⅛ in.
14B	25D	2½ per cent Ni-Cr-Mo (Med. C.)	” ”	”	”	15	30	4 in.
14C	26B	2½ per cent Ni-Cr-Mo (High C.)	” ”	”	”	15	30	Over 4 in.
15A	24F	1½ per cent Ni-Cr-Mo	80–90 ton alloy steel	”	80 min.	14	25	1⅛ in.
15B	25E	2½ per cent Ni-Cr-Mo (Med. C.)	” ”	”	”	14	25	2½ in.
15C	26C	2½ per cent Ni-Cr-Mo (High C.).	” ”	”	”	14	25	Over 2½ in.
16A	24G	1½ per cent Ni-Cr-Mo	100 ton alloy steel	”	100 min.	8	8	1⅛ in.
16B	25F	2½ per cent Ni-Cr-Mo (Med. C.).	” ”	”	”	10	10	2½ in.
16C	26D	2½ per cent Ni-Cr-Mo (High C.).	” ”	”	”	10	10	4 in.
16D	30	4½ per cent Ni-Cr	” ”					
17	31	1 per cent Car-Cr	Ball race steel	”	”	12	15	All
18A	32	Carbon	Carbon case-hardening steel	”	—	—	—	
18B	32	”	” ”	Refined and hardened	32 min.	20	40	—
19A	33	3 per cent Ni	45 tons case-hardening steel	Hardened or refined and hardened.	45 min.	18	40	—
20A	36	3 per cent Ni-Cr	55 tons case-hardening steel	”	55–75	15	35	—
20B	38	5 per cent Ni	” ”	”	65	13	30	—
21	39	4¼ per cent Ni-Cr	85 tons case-hardening steel	”	85 min.	12	25	—

22A	41B	1½ per cent Cr-Al	45–55 ton nitriding steel	H. and T. before nitriding	45–55	20	40	—
22B	40A	3 per cent Cr-Mo	,, ,, ,,	,,	—	—	45	—
23A	41C	1½ per cent Cr-Al	55–65 ton nitriding steel	,,	55–65	17	35	—
23B	—	1 per cent Cr-Mo	,, ,,	,,	—	18	—	—
23C	40C	3 per cent Cr-Mo	,, ,,	,,	—	18	—	—
24	40D	,, ,,	60–70 ton nitriding steel	,,	60–70	17	35	—
25AW	43	Carbon	Vehicle spring steel	W.H. and T.	—	—	—	—
25AC	44	,,	,, ,,	O.H. and T.	—	—	—	—
25BO	45	Si-Mn	,, ,,	,,	—	—	—	—
26A	49	Carbon	Engine valve spring steel	Hard-drawn and blued.	95–120	—	—	—
26B	50	Cr-V	,, ,,	H. and T.	90–100	—	—	—
27A	—	Mn-Ni-Cr	High expansion steel	Softened	40 min.	25	—	—
28	—	36 per cent Ni	Low expansion steel	—	—	—	—	—
29A	51	3 per cent Ni	Engine valve steels	—	—	—	40	—
29B1	52	Si-Cr	,, ,,	H. and T.	—	—	—	—
29B2	53	,,	,, ,,	,,	—	—	12	—
29C	54	Ni-Cr-W	,, ,,	Softened	—	—	15	—
29D	55	Ni-Cr-W	,, ,,	,,	—	—	20	—
30	56	—	Low carbon stainless steel	H. and T.	35–45	25	{ 45 { 25	2 in. Over 2 in.
31A	56	—	Medium carbon stainless steel	—	46–52	20	20–35	—
31B	—	—	,, ,, ,, ,,	H. and T.	55	15	25	—
31C	—	—	Medium carbon stainless steel, free machining	—	—	—	—	—
32	57	—	16 per cent chromium 2 per cent nickel	H. and T.	55	15	25	—
33A	58	18–8	Austenitic stainless	Softened	35	30	50	—
33B	—	,,	,, ,,	,,	—	—	—	—
33C	—	18–8 general purpose	,, ,,	,,	35	25	—	—
33D	—	18–8 higher tensile	,, ,,	Cold-worked	50	20	—	—
33E	—	Higher Cr Higher Ni	,, ,,	Softened	35	30	—	—
33F	—	,, ,,	,, ,,	,,	40	28	40	—

H. and T=hardened and tempered. W.H.=water hardened. O.H.=oil hardened.

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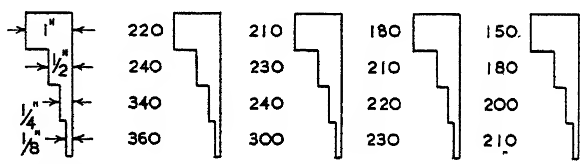
may be said to be pig-iron that has been refined in composition and structure by being remelted, usually with additions of steel scrap, and cast into moulds. Its composition is broadly similar to that of pig-iron but the total carbon and the manganese contents are less and the sulphur content is generally greater; thus what has been said about pig-iron applies also to cast iron.

For most castings a grey iron is required and this is obtained principally by controlling the silicon content. Since rapid cooling tends to retain the carbon in solution and to produce a whitish iron it is more difficult to produce a satisfactory casting when there are wide variations in the thickness of its parts than when it is fairly uniform in thickness. If the silicon content is adjusted to keep the thin parts grey, then the thick parts may be too soft or may be porous or spongy. The behaviour of cast irons and the effect of silicon in this respect is shown up by casting test-pieces of varying thickness as in Fig. 24, in which the numbers



TEST PIECE No.	1	2	3	4
SILICON %	1·1	1·8	2·2	2·6
TENSILE STRENGTH TONS/SQ. IN.	17	14	12	10

FIG. 24.

adjacent to the specimen outlines indicate the Brinell hardness of the corresponding portion of the specimen. Some control over the rate of cooling can be obtained by the use of chills (metal inserts placed in the mould) and by the careful placing of the pouring gates in relation to the mould cavity. For example, if the hot metal passes through the thin sections to get to the thicker ones then the thin sections will not cool down so rapidly as they would do if the reverse was done, since the hot metal will heat up the mould. In the last two decades, however, much progress has been made in controlling the structure of cast irons by means of additions of various elements, of which nickel is, perhaps, the most important. The effect of nickel is somewhat similar to that of silicon in that it tends to keep the carbon in the uncombined or graphitic state and thus to make the iron grey and soft. This action, however, is not accompanied by such great reductions in the tensile strength as are produced by silicon, chiefly because when nickel is present the free carbon is better distributed throughout the mass of metal and the "flakes" of graphite are much reduced in size; it is the presence of large flakes of graphite that bring about the reduction in the tensile strength. A similar result can be brought about by the use of other elements than nickel; for example,

calcium silicide, the use of which is covered by patents, the resulting irons being known by the trade name of *Meehanite*. The high qualities of *Meehanite* irons is, however, not due solely to the use of calcium silicide but also to careful control of all the factors involved in the melting of the iron in the cupola and in the moulding of the casting.

The effect of nickel on cast iron is shown by the test-pieces illustrated in Fig. 25 ; the information on which this figure is based was supplied by the Bureau of Information on Nickel.

Irons containing up to about 2½ per cent of nickel are not usually regarded as being high tensile or special irons ; the latter, which may show tensile strengths up to 35 tons per sq. in., usually contain rather larger percentages of nickel and are made by charging large percentages of steel scrap into the cupola, percentages up to 85 being not uncommon. By these means the total carbon is kept low and the graphite is distributed throughout the mass of metal in a finely divided form, thus

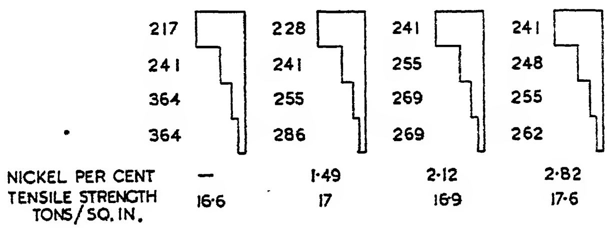


FIG. 25.

enabling the high strengths to be realised. Usually irons made with large percentages of steel scrap have to be poured at higher temperatures than ordinary irons and the operation of the cupola and the moulding technique require considerable experience and careful control if success is to be attained.

Alloy Cast Irons. These, as stated, usually contain more than 2 to 2½ per cent of nickel and the effect of the increase is to harden and strengthen the matrix of the iron, enabling the structure to be made sorbitic or martensitic with rates of cooling that are practicable. The iron can then be heat treated on similar lines to steel so as to modify the structure and obtain the increased strengths desired without undesirable properties such as brittleness. Heat treatment is thus frequently an essential part of the production of high duty cast irons. Percentages of nickel between 2½ and 6 are commonly used in irons for ordinary castings and the heat treatment is usually a quenching in oil from a temperature of about 850° C. followed by a tempering at temperatures up to about 350° C. for the irons containing the lower percentages (2½–4) of nickel, while the irons containing the higher percentages are usually cooled slowly from about 700° C. to make them machinable and, after machining,

are heated to about 800° C. and cooled in an air blast in order to obtain the required strength.

For certain special purposes, such as when corrosion or wear resistance is necessary, it has been found that austenitic steels and irons are the best to use. An austenitic structure can be produced in cast iron by using high percentages (up to 20) of nickel. The use of additional elements such as manganese, copper, chromium, and molybdenum enables similar results to be obtained with smaller percentages of nickel and thus reduces the cost. Thus *Ni-Resist*, which is a patented iron, has a composition as under:

Total carbon	2·7–3·2	Phosphorus	0·4 max.
Silicon	1·0–2·0	Nickel	12–16
Manganese	0·8–1·5	Copper	6–8
Sulphur	0·12 max.	Chromium	1·5–4

The last three elements may conveniently be introduced into the cupola in the form of *N.C.C. pig*, which is a nickel-copper-chromium alloy. Nickel and copper may also be added in the form of *monel* metal (see p. 60).

The austenitic irons, like the manganese steels but to a lesser extent, tend to work harden and this makes it necessary to use lower machining speeds than would otherwise be possible. The compositions and properties of a number of special irons are given in the table on p. 53, which is based on information supplied by the Bureau of Information on Nickel.

The addition of molybdenum to cast iron results in an improvement in the physical properties and percentages between 0·5 and 1·5 are commonly used. When molybdenum is present the carbon content is generally kept down to between 3 and 3·25 and the silicon is limited to about 2·25 per cent. Molybdenum is also used together with nickel, thus the composition

Carbon	3·5–3·8	Manganese	0·5–0·65
Silicon	2·2–2·35	Nickel	0·4–0·5
Chromium	0·8–1·0	Molybdenum	0·4–0·5

has been used for the cast camshafts of motor-car engines. This iron has a tensile strength of about 23 tons per sq. in.

Copper is also frequently added to special cast irons; for example, the compositions used for the cast camshafts and crankshafts of Ford motor-car engines are:

	Carbon	*Silicon*	*Manganese*	*Chromium*	*Copper*	*Phosphorus*
Camshaft	3·3–3·65	0·45–0·55	0·15–0·35	0–0·25	2·5–3·0	0·05 max.
Crankshaft	1·25–1·4	1·9–2·1	0·5–0·6	0·35–0·4	2·5–2·75	0·1 max.

Name and special use of the iron	*Total Carbon*	*Silicon*	*Manganese*	*Nickel*	*Chromium*	*Tensile strength Tons per sq. in.*	*Brinell No.*
Nickel C.I for light sections	3·3	1·8	0·7	1·5	—	18	220
" " medium sections	3·2	1·2	0·7	1·25	—	18	210
Nickel chromium C.I, medium sections	3·2	1·6	0·7	1·25	0·5	18	220
" " " heavy sections	3·2	1·0	0·7	1·25	0·5	18	200
" " " heat resistant	3·2	1·2	0·8	1·0	1·0	17	250
Ni-tensyl, for maximum strength	2·9	1·5	0·8	1·5	—	22	220
Heat-treatable C.I, light sections	3·3	1·6	0·7	2·0	—	25	350*
" " heavy sections	3·2	1·4	0·7	2·5	0·5	25	300*
No-mag, non-magnetic	3·0	1·5	7·0	11·0	—	16	180
Ni-resist, heat and corrosion resistant	3·0	1·5	1·0	14·0	2·0	16	180†
Nicrosilal, maximum heat resistant	1·7	4·5	0·8	18·0	2·0	16	180‡
Lo-expansion C.I	2·2	1·5	0·8	34·0	2·0	14	180

* Heat treatment consists of oil quench from 850° C. followed by tempering at 350° C.

† This contains 7 per cent copper; if the copper is omitted the nickel content must be put up to 22 per cent.

‡ Patented by the British C.I. Research Committee.

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Chapter 3

NON-FERROUS ALLOYS

The non-ferrous materials used in engineering are nearly all alloys, the chief exceptions being copper and aluminium, which are used fairly extensively in the unalloyed state. Non-ferrous alloys are very numerous; they are grouped thus:

1. Brasses—alloys of copper and zinc.
2. Bronzes—alloys of copper and tin.
3. Special brasses and bronzes.
4. Copper-nickel alloys.
5. Bearing alloys.
6. Aluminium alloys.
7. Magnesium alloys.
8. Miscellaneous alloys.

Copper.[1] Three principal types of copper are used in engineering, namely, *high conductivity (H.C.) copper*, *best select copper*, and *arsenical copper*. The three varieties may all be obtained free of oxygen, being then called "de-oxidised" or "oxygen-free"; but normally they contain a small percentage of oxygen, and are then known as "tough-pitch." *H.C. copper* is 99·9 per cent copper, and has the highest electrical and thermal conductivities obtainable in the metal; *best select copper* contains small amounts of various impurities, but is suitable for most purposes; *arsenical copper* contains up to about 0·5 per cent of arsenic, which improves the mechanical properties.

Copper can be, and is, cast, but its mechanical properties are greatly improved by rolling, forging, etc., and it is used chiefly in the cold-rolled and annealed state. Typical values for the mechanical properties are given in the table below:

Condition	*Ultimate strength Tons per sq. in.*	*Elongation on 2 in. Per cent*	*Brinell No.*
As cast	10–11	25–30	40–45
*Cold-worked	20–26	5–20	80–100
*Cold-worked and annealed	14–16	50–60	45–55

* These figures apply to sections exceeding $\frac{1}{8}$ in. in thickness.

When heavily worked, as, for example, in wires, the tensile strength may be as high as 30 tons per sq. in., the elongation being then only 1–5 per cent.

Brasses. These may be subdivided into

(*a*) The α-brasses, containing up to about 37 per cent zinc;
(*b*) The α–β-brasses, containing between 40 and 44 per cent zinc.

[1] The information contained in this article is based on data contained in a publication of the Copper Development Association.

The α-brasses are capable of being cold-worked to a remarkable extent, and may be rolled, pressed, and drawn. They can also be worked hot, but not nearly so readily as cold, while the presence of quite small amounts (0·1 per cent) of impurities such as lead will make them "hot-short." Two "qualities" of brass are commonly used, *basis quality*, containing about 63 per cent copper and 37 per cent zinc, and *cartridge brass*, containing about 70 per cent copper and 30 per cent zinc. A variation of the latter is *Admiralty brass*, whose composition is 70 per cent copper, 29 per cent zinc, and 1 per cent tin. In the annealed state cartridge brass has an ultimate strength of about 20 tons per sq. in., an elongation of about 70 per cent on 2 in., and a Brinell hardness of about 60. Cold-working hardens the α-brasses and reduces their ductility; thus, hard-rolled sheet gives an ultimate strength of about 35 tons per sq. in., an elongation of about 12 per cent, and a Brinell hardness of between 150 and 200. Four "tempers" are commonly recognised as being imparted to brasses by various amounts of cold-working; they are: (1) *Soft*; (2) *Quarter* to *half-hard*; (3) *Hard*; (4) *Extra* or *spring hard*.

The annealing of brasses is a re-crystallisation process, during which new small crystals are formed. This re-crystallisation does not occur at temperatures below 280° C., and heating to within this limit is done merely as a stress-relieving operation. At temperatures over 400° C. grain growth may occur if the heating is unduly prolonged. Annealing is usually done at temperatures between 300° and 600° C., and the material may be quenched in water, or cooled in air, afterwards, the rate of cooling being unimportant.

Articles made of α-brasses that have been cold-worked often exhibit what is called *season-cracking*—the formation of cracks some time after manufacture and without the application of any external load. This is due to the internal stresses left in the material by the cold-working, and is accelerated by corrosive atmospheric conditions. It can be obviated by stress-relieving the articles by heating them to between 250° and 275° C. for half an hour to one hour. As mentioned above, this treatment has no effect on the mechanical properties of the brasses.

Brasses do not show any well-marked yield point or elastic limit, and so it is common practice to specify a proof stress (see Chap. 1).

The α–β-Brasses. When the zinc content exceeds 39 per cent, a second constituent (the β-form) appears in the microstructure of brass. This constituent makes the brass readily workable while *hot*. When the zinc content exceeds 49 per cent a third constituent (the γ-form) appears; but brasses containing this constituent are rarely used. The α–β-brasses containing between 39 and 44 per cent of zinc are, however, widely used for hot-pressings, stampings, etc. One of the best known and earliest examples is that known as *Muntz metal*, whose composition is approxi-

mately 60 per cent copper and 40 per cent zinc. It is somewhat difficult to machine, but this can be remedied to a large extent by the addition of up to 3 per cent of lead. The lead, however, makes the metal hot short at about 550° C. and at temperatures above 750° C., so that it can be forged only between 650° and 750° C. Lead is not soluble in copper or zinc, and remains merely distributed throughout the mass; trouble is consequently sometimes experienced from undue segregation. Muntz metal hot-stampings will give an ultimate strength of about 22–25 tons per sq. in. and an elongation of about 30 per cent on 4 in. *Naval brass* is approximately Muntz metal plus 1–1½ per cent tin.

Bronzes. These are alloys of copper and tin; although up to 16 per cent of tin may be retained in solution in copper if the alloy is cooled very slowly, the amount that can be retained with practical rates of cooling is about 8 per cent. Bronzes containing up to 8 per cent of tin correspond, therefore, roughly to the α-brasses; they can be cold-worked, but not so easily as the brasses. Tin contents greater than 8 per cent are used for castings and small amounts of phosphorus are sometimes added to help in the elimination of tin oxide and to improve the mechanical properties. Excess of phosphorus leads to brittleness and normally the content is only about 0·05 per cent; in true *phosphor bronze* the phosphorus content is from 0·1 to 0·5 per cent. In the form of castings phosphor bronze will give an ultimate strength of about 18 tons per sq. in. with an elongation of about 4 per cent. The wrought bronzes will give ultimate strengths of 22–24 tons per sq. in. with elongations of about 60 per cent in the annealed state, while in the worked condition the ultimate strength may be as high as 50–60 tons per sq. in.

Gun Metal. This is an alloy of copper, tin, and zinc and is widely used for castings, particularly when they are of complicated form. A common composition is copper 88, tin 10, and zinc 2 per cent, and this will give an ultimate strength of about 17 tons per sq. in. together with an elongation of about 20 per cent.

Special Brasses and Bronzes. Additions of manganese, nickel, iron, aluminium, and some other elements improve the properties of brass and bronze and are widely used. In brasses the resulting materials are generally known as *high tensile brasses*, but the name bronze is often misapplied. An example of a high tensile brass is *delta metal*, which is an α–β-brass containing about 2 per cent of iron and 1 per cent of manganese; this alloy may be cast, may be worked hot (above 500° C.), is resistant to corrosion, and has mechanical properties that make it a useful substitute for mild steel. Another example is *manganese bronze*; this is an *α–β-brass* plus 1–2 per cent of manganese and, sometimes, 2–3 per cent of nickel and up to 4 per cent of aluminium. Tensile strengths

from 30 to 35 tons per sq. in., together with elongations of 10–35 per cent, can be obtained and the properties can sometimes be improved by heat treatment. Manganese bronzes can be forged and hot stamped between 600° and 750° C. but are hot short at higher temperatures; they are subject to undue grain growth if held for too long between 700° and 800° C. and the mechanical properties are then greatly reduced; this cannot be remedied except by re-melting.

In recent years much progress has been made in the development of brasses that can be heat treated so as to be made soft for working and then hardened and improved in mechanical properties. One such alloy has the composition, copper 72 per cent, nickel 6 per cent, aluminium 1½ per cent, and zinc 20½ per cent; it may be annealed by quenching in water from 850° C. and hardened by re-heating to about 500° C. and cooling slowly. Its properties are shown in the table below:

Condition	*Ultimate strength Tons per sq. in.*	*Proof stress Tons per sq. in.*	*Elongation Per cent*
Annealed	23	5	60
Heat treated	36	22	30
Heat treated after cold working	48	45	11

The aluminium content also improves the corrosion resistance. This alloy should be compared with the copper-nickel alloys on p. 60.

Aluminium Bronzes. This name has been given to alloys of copper with up to 12 per cent of aluminium and, sometimes, nickel, manganese, and iron. The copper-aluminium alloys containing less than about 7 per cent of aluminium possess great ductility; for example, an alloy containing 4 per cent of aluminium will give an elongation of 80 per cent on 2 in.; these alloys may consequently be readily worked cold. Alloys containing from 8 to 12 per cent of aluminium are used for castings and will give a tensile strength of about 30 tons per sq. in. and an elongation of 20–40 per cent on 2 in. in the sand-cast state. When die-cast the tensile strength is some 30 per cent higher. The alloys are susceptible to a heat treatment consisting of quenching and tempering, as is shown by the tables below and which relate to an alloy containing about 9·5 per cent of aluminium.

Quenching temperature ° C.	*Ultimate strength Tons per sq. in.*	*Elongation on 2 in. Per cent*	*Izod value Kg-m.*	*Brinell No.*
(*Slowly cooled*)	36·5	33	1·6	175
550	37·0	33	1·7	173
650	40·0	43	5·1	160
750	45·0	32	4·1	217
850	54·5	17	3·2	218
950	58·0	5	5·2	218

Condition	*Ultimate strength Tons per sq. in.*	*Elongation on 2 in. Per cent*	*Proof stress (0·1 per cent) t.s.i.*	*Diamond pyramid hardness*
Hot worked and drawn .	33·4	28	15·4	178
Heated 1 hour at 900° C. and quenched . . .	48·6	29	12·6	187
Quenched from 900° C., tempered 1 hour at 400° C.	48·5	29	13·7	185
Quenched from 900° C., tempered 1 hour at 600° C.	45·2	34	15·4	168
Quenched from 900° C., tempered 1 hour at 650° C.	41·8	48	14·4	150

These alloys have excellent corrosion-resisting properties, being practically equal in this respect to an 80/20 cupro-nickel (see p. 60); their corrosion-fatigue properties are also very good. They are suitable for gravity die-casting but require special treatment when cast in sand moulds, partly because they have a very narrow freezing range and partly because they absorb gases and oxides rather readily when molten; thus generous risers and non-turbulent gating are necessary (see Chap. 4).

The compositions of the more complex aluminium bronzes are commonly aluminium 9–11, nickel 3–5, manganese up to 1, iron up to 5 per cent, the balance being copper. In the form of sand-mould castings they will give the following properties: ultimate strength, 35–45 tons per sq. in.; elongation, 30–15 per cent; Brinell, 120–150. By quenching from 850° C. and tempering at between 600° and 650° C. the ultimate strength may be raised to between 44 and 50 tons per sq. in., the elongation being reduced to 15–5 per cent.

Nickel Bronzes. These are of two types: (*a*) *low nickel*, and (*b*) *high nickel.* The former contain 3–5 per cent of nickel, 5–10 per cent of tin, and 0–2 per cent of zinc, and in the form of sand-mould castings will give an ultimate strength of 18–24 tons per sq. in. with an elongation of 20–10 per cent. The high nickel bronzes contain 15–60 per cent nickel, 6–12 per cent tin, 1–2 per cent zinc, up to 3 per cent silicon, and 0·1 per cent magnesium. They will give, in the sand-cast state, ultimate strengths up to 30 tons per sq. in.

Copper Leads or "Lead Bronzes." These names have been given to a series of alloys of copper and lead with or without tin. They may be divided into three groups: (*a*) those containing 5–10 per cent of tin and 8–10 per cent of lead, which are used for castings for heavily loaded sliding members, slide-valves, bearings, etc.; (*b*) those containing up to 35 per cent of lead and only about 5 per cent of tin; these are sometimes called *plastic bronzes*, they have little strength and are used chiefly as linings to bearings, shells being used to support them. The

third group comprises the alloys in which very little or no tin is used and these are dealt with under Bearing Alloys on p. 62.

Copper-Nickel Alloys. Nickel and copper alloy together in all proportions so that the range of copper-nickel alloys is extremely wide. The addition of nickel to copper improves the mechanical properties and increases the resistance to corrosion. Up to 2 per cent of nickel is consequently now commonly added to copper for such things as locomotive firebox stay rods ; in special circumstances up to 12 per cent has been used. When the nickel content is between 15 and 30 per cent the alloy has remarkable drawing properties, and is used for the sheaths or envelopes of rifle bullets ; these alloys are called *cupro-nickels.* A 70/30 cupro-nickel is widely used for condenser tubes as it has been found to have outstanding resistance to corrosion and erosion. These tubes are produced by an extrusion process followed by cold reduction in dies. The mechanical properties of the alloy are given in the table below :

Condition	*Elastic limit Tons per sq. in.*	*Ultimate strength Tons per sq. in.*	*Elongation on 2 in. Per cent*	*Brinell No.*
As drawn . . .	8	38	9	140
Drawn and annealed	6	28	44	90

Its fatigue strength is $\pm 11{\cdot}6$ tons per sq. in. in the annealed state and $\pm 15{\cdot}6$ tons per sq. in. after cold working and stress relieving.

Higher nickel contents, between 40 and 45 per cent, give alloys possessing exceptionally high electrical resistance ; for example, *Constantin* and *Eureka.*

Monel Metal. This is one of the most widely used and remarkable of the nickel-copper alloys. It contains about 70 per cent nickel, up to 4 per cent iron, up to 2 per cent manganese, and traces of other elements, the balance being copper. It possesses very high corrosion resistance coupled with excellent mechanical properties, the latter, which are better than can be obtained with most other non-ferrous alloys, being well maintained at high temperatures. Monel metal can be cast and can also be worked both hot and cold ; its mechanical properties are given in the table below. Recent researches have shown that, as with the nickel bronzes, additions of certain elements will make monel metal amenable to heat treatment. The elements used are aluminium, silicon, and beryllium and the hardening is a " precipitation " process, which occurs briefly as follows. The elements combine with nickel to form compounds that are normally insoluble in the monel metal base at ordinary temperatures but which can be retained in solution by rapid cooling. When the compounds are in solution the alloy is soft and readily workable, but when they are precipitated out, by heating to between 400° and 500° C. and cooling comparatively slowly, the alloy is hardened and its mechanical properties are improved. Cold working

also increases the strength and hardness but, of course, reduces the ductility. The relative properties of ordinary and heat-treated monel metal are shown by the following table:

	Condition	*Ultimate strength Tons per sq. in.*	*Elongation on 2 in. Per cent*	*Reduction of area Per cent*	*Brinell No.*
A	Annealed	31·3	50·0	72	120
A	Cold drawn, 26 per cent. reduction of area	50·2	19·5	64	200
A	Cold drawn, 26 per cent. reduction of area, stress relieved	52·3	22·0	60	205
B	Quenched in water from 800° C.	35·0	45·0	65	143
B	Quenched in water from 800° C. and reheated	60·0	30·0	45	270
B	Water quenched, cold-drawn (15 per cent reduction of area) and reheated	76·0	20·0	30	310

A=Ordinary *Monel* metal. B=Heat-treatable *Monel* metal.

In castings silicon is used to make the alloy heat-treatable and its effect is shown by the table below.

Alloy	*Ultimate strength Tons per sq. in.*	*Elongation Per cent*
Ordinary *monel* metal	24	18
,, ,, plus 2·75 per cent Si	38	16
,, ,, plus 3·75 per cent Si	45	5

The effect of rate of cooling with these alloys is just the opposite to the effect with cast iron; thus, slow cooling will produce the harder, stronger structures, while rapid cooling by means of chills will produce softer, weaker metal.

The addition of aluminium, silicon, and beryllium to copper-nickel alloys containing up to about 30 per cent of nickel produces alloys that are heat-treatable and which have high corrosion resistance, though not to the same extent as monel metal. For example, an alloy containing 30 per cent nickel, 1½ per cent aluminium, and the balance copper, gives an ultimate strength of 27 tons per sq. in. in the annealed (water quenched) state, and this value is raised to about 48 tons per sq. in. by reheating; if cold work is done on the alloy before reheating the strength may be raised as high as 56 tons per sq. in. The table below shows the effects of silicon and beryllium on an alloy containing 80 per cent copper and 20 per cent nickel, and also the properties of an alloy containing only 6½ per cent of nickel. Generally speaking the corrosion resistance of the copper-nickel alloys improves as the precentage of nickel increases.

Alloy	*Ultimate strength Tons per sq. in.*	*Elongation Per cent*	*Brinell No.*
Cu, 80%; Ni, 20%; Si, 0·24%	35	65	140
Cu, 79%; Ni, 20%; Be, 1·0%	51	9	218
Cu, 92%; Ni, 6½%; Al, 1½%	44	20	—

Nickel Brass or Nickel "Silver." These names, and also the name *German silver*, are applied to alloys of copper, zinc, and nickel; the copper/zinc ratio is generally about 70/30 while the nickel content ranges from 5 to 30 per cent. The alloys have a silvery appearance and possess very good resistance to atmospheric oxidation and corrosion, hence they find a wide use in both engineering and commercial applications. The table below gives some typical compositions.

Copper	65	65	64	62	55
Zinc	25	20	18	33	27
Nickel	10	15	18	5	18

Recently it has been found that, as with monel metal and the high tensile brasses, the addition of aluminium makes these alloys heat-treatable.

Bearing Alloys. It has been found that the most suitable material for use in many bearings is one in which grains or blocks of a hard constituent are embedded in a matrix of comparatively soft material. This is because the soft matrix permits the bearing to deform sufficiently to conform to the journal or shaft, while the hard blocks keep the wear low. The soft matrix also absorbs any particles of foreign matter that may get into the bearing and thus prevents scoring of the journal. Most of the bearing alloys now in use have this type of structure.

The structure is obtained in phosphor-bronze, but the matrix material is too hard for these alloys to be satisfactory in heavily loaded, high-speed bearings, such as big-end and main bearings of high-speed internal combustion engines. For lighter duties, however, phosphor-bronze is much used; the tin content may range from 5 to 20 per cent but usually is between 10 and 12 per cent, phosphorus is between 0·05 and 1·0 per cent, and up to 20 per cent of lead may be included. Phosphor-bronze bushes are sometimes made by moulding a mixture of copper and tin, in powder form, in presses under heavy pressures (up to 40,000 lb. per sq. in.), heating up to about 700° C., and cooling in air or quenching in oil. These bushes, being slightly porous, can retain oil in the pores, thus making them self-lubricating over long periods. Graphite may also be included in the mixture of powders.

For heavy duty bearings *white-metal* alloys or copper-lead alloys are now generally used. The oldest white metal is *Babbitt's metal*, which contains about 85 per cent of tin, 5 per cent of copper, and 10 per cent of antimony. The antimony, in the form of a solid solution in some of the tin, provides the hard blocks or grains; these blocks, being lighter than the matrix metal, tend to float to the surface, but this is largely prevented by the formation of a compound of copper and tin which, being present in the form of a mass of needle-like crystals, entangles the antimony-tin blocks and thus prevents undue segregation. Because tin is very expensive attempts have been made to develop white metals

containing smaller percentages than are used in Babbitt metal, and metals containing 75–85 per cent of lead, 5–15 per cent of antimony, and only 5–12 per cent of tin are now in use. The percentage of antimony is generally between 10 and 12 and this element again provides the hard blocks in the structure. Broadly speaking the higher the lead content the less severe the duty the bearings can withstand.

In recent years " alloys " of lead and copper (misnamed lead " bronzes ") have been developed and have largely displaced white metals in high duty bearings. These alloys contain from 25 to 45 per cent of lead, from 60 to 75 per cent of copper, and small amounts of other elements ; for example, up to 1 per cent of tin or 1–1½ per cent of nickel and up to 0·5 per cent iron.

Lead and copper do not dissolve in each other at all and lead bronzes are merely mixtures of the two metals. Segregation is, therefore, a difficulty that is commonly met in the production of copper-leads, but with suitable casting or melting techniques it can be avoided.

Alloys of copper, lead, and silver have been used to some extent for bearings, and alloys of cadmium, silver, and copper are in fairly extensive use ; a typical alloy has the composition 97·5 per cent cadmium, 2·25 per cent silver, and 0·25 per cent copper ; this alloy is said to have a higher fatigue strength than Babbitt metal but to suffer from liability to corrosion if organic acidic compounds are present in the lubricating oil. This corrosion trouble has also been experienced, to some extent, with lead-bronzes. A cadmium alloy containing about 1½ per cent of nickel has also been used.

The most recently developed bearing alloys are the aluminium base alloys such as the *Quartzal* alloys developed in Germany and the alloys developed by Rolls-Royce, Ltd. The former contain from 2 to 15 per cent of copper ; the latter have the compositions : (*a*) Tin 5·5–7, nickel 1·4–1·7, magnesium 0·7–1, copper 0·6–0·9 per cent ; and (*b*) Tin 4·6–5, nickel 1·6–2, magnesium 0·35–0·5, antimony 0·4–0·8, manganese 0·7–0·9, and silicon 0·45–0·6 per cent, the balance in each composition being aluminium. The first composition (*a*) is used for big-end bearings and the second (*b*) for main bearings. These alloys are said to retain their hardness at the temperatures ordinarily met in bearings much better than other bearing alloys and their initial hardness is over twice that of the copper-lead alloys.

Aluminium Alloys. Pure aluminium is too soft, and its tensile strength is too low, for it to find much use in engineering applications but it is extensively used in a 99·9 per cent pure state for such things as motor-coach body panels, trimming, and fittings, and for architectural and domestic purposes. Additions of certain elements, however, improve the mechanical properties so much that, weight for weight, aluminium alloys are equal in strength to the best alloy steels and are

consequently very widely used. The principal alloys may be grouped as follows:

1. Aluminium-copper alloys.
2. Aluminium-zinc-copper alloys.
3. Aluminium-silicon alloys, sometimes with copper in addition.
4. Alloys 1, 2, or 3 with additions of magnesium, manganese, nickel, iron, or tin.
5. Complex alloys, duralumin, Y-alloy, the R.R. alloys, etc.

The Aluminium-Copper Alloys. The addition of copper hardens and strengthens aluminium, the tensile strength increasing steadily with the copper content up to about 8 per cent of copper, beyond which point little improvement occurs. Up to 12 per cent is, however, used because the machining properties of the alloy are improved by the higher copper content. Two alloys in this group are widely used for castings; one contains about 12 per cent of copper and the other from 6 to 8 per cent. The properties of the latter can be improved by a heat treatment consisting of heating to about 540° C. and quenching in water but the improvement does not occur until some days after the treatment. This delayed action is known as *ageing* and is characteristic of many aluminium alloys. The time required for ageing can often be reduced from several days to a few hours by heating the article in boiling water. The ultimate strength of the 6–8 per cent copper alloy in the "as cast" condition is about 11 tons per sq. in. and this increases after heat treatment and ageing to about 20 tons per sq. in.

The explanation of ageing is generally accepted to be as follows: Copper can be retained in solution in aluminium to the extent of only 1–2 per cent at atmospheric temperatures but to the extent of about 6 per cent at 540° C.; hence, a slowly cooled 6 per cent copper alloy will consist of crystals of aluminium, with about 1½ per cent of copper in solution, surrounded by a network of a copper-aluminium compound ($CuAl_2$) containing a higher percentage of copper. By heating to 540° C. for some hours a good deal of the compound will be broken up and its copper will go into solution in the aluminium. By quenching in water this copper may be retained in solution, but not indefinitely, because the quenched alloy is unstable and the excess copper is ultimately precipitated in a very finely divided form; this gives the resulting material its improved mechanical properties. Magnesium, in the presence of silicon, with which it can combine to form Mg_2Si, acts in a similar manner and so does lithium. Iron tends to check the precipitation but this action is reduced by the presence of silicon, which combines with the iron.

Aluminium-Zinc-Copper Alloys. The addition of zinc also hardens aluminium, but when the percentage exceeds about 13 the alloy suffers from hot shortness and is thus unsuitable for castings. This hot shortness can be eliminated by the introduction of 2½–3 per cent of copper and an alloy containing 13–14 per cent zinc and 2½–3 per cent copper is

widely used. It has an ultimate strength of between 11 and 16 tons per sq. in.

Aluminium-Silicon Alloys. In these alloys the silicon content ranges from 5–15 per cent and the alloys possess work-hardening properties. Thus aluminium-silicon sheets are supplied in three "tempers," *hard*, *medium*, and *soft*, according to the amount of work done on them during the rolling process. The properties of the three grades are shown in the table below.

Grade	*Ultimate strength Tons per sq. in.*	*Elongation Per cent*
Hard	12–14	9–15
Medium	10–12	15–10
Soft	9–10	30–20

When the silicon content is between 8 and 15 per cent the properties of castings may be improved by putting a small quantity of an alkaline metal, an alkaline-earth metal, or one of their compounds, into the molten metal immediately before pouring. Sodium is commonly used and the result is a great refinement in the structure of the material, the addition apparently checking the growth of the first crystals formed and keeping them small in size. The process is known as *modification.* Thus a 13 per cent silicon alloy cast in the ordinary way might show an ultimate strength of only 6–8 tons per sq. in. and an elongation of only 0·5–1·25 per cent. If modification is done then this alloy might show an ultimate strength of 12–16 tons per sq. in. and an elongation of 7–15 per cent. The modified alloys are very malleable in the as-cast condition; they also shrink less than most other alloys during solidification and this helps in the production of sound castings.

Examples of alloys coming in this group are *Alpax*, the alloy generally known as *L.*33, and the alloy known as *Lautal.* Alpax is similar to L.33 which contains 10–13 per cent silicon and, when cast in sand moulds, has an ultimate strength of about 10 tons per sq. in. and an elongation of about 5 per cent. Lautal, which contains 4 per cent of copper and 2 per cent of silicon, does not age at room temperatures but requires to be heated for periods up to 16 hours at between 120° and 130° C. It is supplied by the manufacturers in four grades, the properties of which are tabulated below:

Grade	*Ultimate strength Tons per sq. in.*	*Elongation Per cent*	*Brinell No.*
Normal	24–27	25–18	90–100
Unhardened	19–22	25–18	70–80
Soft annealed	14–15	28–20	50–55
Hard rolled	28–38	15–3	100–135

The tensile strength in the as-cast condition is comparatively low and the figures quoted above are for rolled sheets that have had considerable work done on them. The unhardened grade can be brought to the

normal condition by heating to between 120° and 130° C. for 16 hours. Annealing is done by heating to between 350° and 400° C. and cooling slowly; annealed material can be brought to the unhardened condition by heating to between 490° and 510° C. and quenching in water. Other elements that are used in aluminium-copper, aluminium-copper-zinc, and aluminium-silicon alloys are magnesium, manganese, nickel, iron, and tin.

Duralumin. This is one of the oldest and best known aluminium alloys and is widely used in the form of forgings, pressings, and rolled sections but is not suitable for castings. Its composition is copper 3·5–4·5, manganese 0·4–0·7, silicon about 0·4 per cent and, sometimes, magnesium 0·4–0·7 per cent. Iron is usually present but must be kept below 0·5 per cent. Duralumin can be worked readily at temperatures of about 500° C. and after quenching ages over a period of 4–5 days.

Y-Alloy. This has the composition copper 4, magnesium 1·5, and nickel 2 per cent. It may be forged but is most widely used for castings. To develop its best properties it must be quenched in boiling water from a temperature of about 515° C. and then be aged at room temperature for about 5 days or in boiling water for about 2 hours. Its ultimate strength is about 14 tons per sq. in. in the cast and heat-treated form but chill castings, after heat treatment, may show a strength of 20 tons per sq. in. The alloy maintains its strength well at high temperatures and is widely used for the pistons of internal combustion engines. Heat treated forged Y-alloy will give an ultimate strength of 23–27 tons per sq. in., an elongation of 17–22 per cent, and a Brinell hardness of 100–105. Y-alloy should never, in melting, be raised to a temperature higher than 750° C.

The R.R. Alloys. These have been developed by Rolls-Royce, Ltd., and are manufactured by High Duty Alloys Ltd. The chief alloys are four in number and their compositions and properties, after heat treatment, are given in the table below:

Alloy	*Cu*	*Ni*	*Mg*	*Fe*	*Ti*	*Si*	*Ultimate strength Tons per sq. in.*	*Elongation Per cent*	*Brinell No.*
R.R.50 . . .	1·30	1·3	0·1	1·0	0·18	2·20	11	3	70
R.R.53 . . .	2·25	1·3	1·6	1·4	0·10	1·25	24	1	130–150
R.R.56 . . .	2·00	1·3	0·8	1·4	0·10	0·70	30	10–20	120–160
R.R.59 . . .	2·25	1·3	1·6	1·4	0·10	0·50	24	8	130

These alloys are used respectively for general castings, die-castings (especially pistons), general forgings, and forged pistons. The heat treatments given to the four alloys are all similar and consist of heating to between 510° and 540° C. for 2–4 hours, quenching in water, reheating to between 155° and 175° C. for 10–20 hours, and finally quenching in water. For the R.R.50 alloy the first heating and quenching are omitted.

The R.R.53 and R.R.59 alloys maintain their properties well at high temperatures.

Classification of Aluminium Alloys. A useful method of classifying aluminium alloys is according to their mechanical strength and, when this is done, they are found to fall roughly into three groups as indicated in the Table below.

ALUMINIUM ALLOYS

Condition	*Low strength*			*Medium strength*			*High strength*		
	0·1 per cent proof stress	*Ultimate strength*	*Per cent elongation*	*0·1 per cent proof stress*	*Ultimate strength*	*Per cent elongation*	*0·1 per cent proof stress*	*Ultimate strength*	*Per cent elongation*
Sheets . .	5	5–9	5	7–27	11–30	2–25	14–21	20–27	8–15
Extrusions .	2–5	5–8	25–40	7–14	11–24	15–25	14–27	18–33	8–15
Forgings . .	—	—	—	7–19	12–25	8–25	14–26	19–30	6–20
Castings . .	3–8	7–16	0–10	6–13	7–17	2–12	11–25	14–28	0–15

Magnesium Alloys. The only magnesium alloys of any importance are those known by the trade name *Elektron.* Of these there are several compositions, each used for certain particular purposes and each possessing special properties. One alloy, used for castings, has the composition aluminium 9–11, zinc less than 3·5, manganese less than 0·5, impurities less than 1·5 per cent, the balance being magnesium. This alloy has an ultimate strength of about 8 tons per sq. in. For rolling into bars an alloy is used which has the composition aluminium 11 per cent, zinc less than 1·5 per cent, manganese less than 1·0 per cent, impurities less than 1·5 per cent. This alloy will show an ultimate strength varying from as high as 17 tons per sq. in. in the smaller sections down to about 14 tons per sq. in. in the larger sections. For extruding into bars an alloy containing not more than 0·2 per cent aluminium and not more than 2·5, 0·2, 0·2, 0·4, and 0·5 per cent respectively, of manganese, zinc, copper, silicon, and impurities is used. This will give a proof stress of 8 tons per sq. in. and an ultimate strength of about 15 tons per sq. in. with an elongation of about 2 per cent. For general forgings the composition aluminium 7·5–8·5, zinc 0·4–0·55, manganese 0·15–0·25 is used and will give a proof stress of 11–14 tons per sq. in. and an ultimate strength of 18–22 tons per sq. in., a reduction of area of about 10 per cent and a Brinell hardness between 65 and 75.

Elektron can be worked cold only to a very limited extent but at a temperature between 270° and 330° C. it may be worked readily. It is the lightest alloy known at present and is used extensively in aeroplane

construction. It is poor in resistance to corrosion and must be protected by some surface treatment such as, for example, the R.A.E. chromate treatment or by painting.

Miscellaneous Non-Ferrous Alloys. Pressure Die-Casting Alloys. The principal die-casting alloys are those having zinc, aluminium, lead, or tin as the base metal; the first two are much more widely used than the last two. Lesser used base metals are copper and magnesium.

Two commonly used zinc base compositions are: (*a*) copper 2·5–3·5, aluminium 3·5–4·5, magnesium 0·02–0·10 per cent; and (*b*) Copper 0·1 max., aluminium 3·5–4·5, magnesium 0·03–0·08 per cent, zinc forming the balance in each alloy. The alloy with the higher copper content has a higher tensile strength but is not so stable as the other alloy and its properties, particularly its impact strength, deteriorate as ageing occurs. Zinc base alloys are very susceptible to inter-crystalline corrosion and to avoid this impurities must be kept to a very low percentage; it is necessary, therefore, to use zinc whose purity is at least 99·99 per cent. Zinc base alloys shrink dimensionally at first but then grow over a period of 4–5 weeks; this sometimes prohibits their use but the effect can be eliminated by annealing at 100° C. for 4 hours, cooling in air. The alloys cannot withstand temperatures in excess of about 150° to 200° C. but they take a very good finish and, being cast at comparatively low temperatures, can be cast in soft, mild-steel dies. Thus they are cheaper, other factors being the same, than most other die-casting alloys.

Several aluminium alloys are used for die casting, but four of the most important are the following: Aluminium-copper, aluminium-silicon, aluminium-silicon-copper, aluminium-silicon-copper-nickel. Typical compositions for these are given below:

Copper .	—	—	2	4	1·5	4·0	8·0	Aluminium balance
Silicon .	5	12	3	5	1·0	1·75	1·5	
Nickel .	—	—	—	—	2·25	4·0	—	

The aluminium base alloys are more stable dimensionally, and will stand higher temperatures than the zinc base alloys; they are also free from inter-crystalline corrosion and retain their strength well at temperatures below zero. As their casting temperature is higher than that of zinc base alloys, soft steel dies have a shorter life and an alloy steel may have to be used. They also require larger dimensional tolerances and cannot be cast in quite such thin sections.

Solders. These are divisible into two groups: (*a*) soft solders, and (*b*) hard solders. The principal soft solders are lead-tin alloys; thus *tinsmith's solder* ranges from about 40 per cent to about 70 per cent tin. A composition—tin 63 per cent, lead 37 per cent—gives the eutectic alloy, which melts at 183° C. British Standard Grade B solder has the composition, tin 50 per cent, antimony 2·5–3 per cent, lead 47·5–47

per cent. This is the type of solder used for most manufacturing work. *Plumber's solder* has the composition, lead 70 per cent, tin 30 per cent; it freezes over a wide range of temperature and, being pasty between the beginning and end of solidification, is suitable for making "wiped" joints. Tinsmith's solder is always used with a flux, whose function is to render fluid the oxides produced and to form a film over the surfaces being joined so that the oxides can be kept away. The chief fluxes are "killed spirits" or zinc chloride, ammonium chloride, resin, and tallow. Cored solder, in which the flux forms the core or cores, is obtainable and is being more and more used.

When hard solders are used the process is sometimes called *brazing* and the solder is then called *spelter*; a common composition for spelter is copper 50 per cent, zinc 50 per cent, but up to 1·0 per cent of silver is sometimes included. Another hard solder is that known as *silver solder*; this consists of 10 per cent nickel, 40–50 per cent zinc, the balance being copper. The flux commonly used for brazing and silver soldering is powdered borax. For methods of soldering, see Chap. 7.

Low Melting Point Alloys. Alloys which melt at low temperatures, ranging from 60° up to 200° C., are of great use for certain purposes and numerous alloys have been developed. One of the oldest and most used is *Wood's metal* which melts at 60·5° C. It consists of bismuth 50, lead 25, tin 12½, cadmium 12½ per cent. Another is *Rose's metal* which is the same as Wood's, except that the cadmium is replaced by tin; it melts at 93·7° C. *Cerromatrix*, an alloy developed by the Cerro de Pasco Copper Corporation, has the composition, bismuth 48 per cent, lead 28·5 per cent, tin 14·5 per cent, and antimony 9·0 per cent. It melts over the range of temperature 102·5°–227° C. and expands on solidification. Among other uses it is used for setting press-tool punches into their holders.

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Chapter 4

THE PRODUCTION OF CASTINGS

Castings are made by pouring molten metal into moulds and allowing it to solidify. The mould is usually made by means of a pattern. Thus the making of a casting involves:

1. The making of the pattern.
2. The making of the mould.
3. The preparation of the molten metal.

In addition, all castings require some "cleaning up" before they can be sent to the machine shops; this cleaning up is known as *fettling* and forms a fourth operation in the production of a casting. Pattern making is a skilled trade in itself and a knowledge of its technique, though useful to an engineer, is not essential; space is not available to deal with it in this book and for information about it reference should be made to books on pattern-making. The art of making the moulds also forms a separate skilled trade but some knowledge of the technique involved is desirable, if not essential, for an engineer or designer, because moulding difficulties are sometimes limitations to which the designer must conform and also the designer can often simplify the moulding process by modification of his design, and unless he is aware of the difficulties he cannot help the moulder in this way. Moulding technique will, therefore, be considered; it should, however, be understood that the treatment of the subject is not intended to be adequate for an engineer whose work lies in a foundry but only for those whose designs and products involve the use of castings, to enable them to appreciate the moulder's difficulties and to be able to minimise them as far as possible. The preparation of the molten metal is also an art, although considerable progress has been made towards making it a science, and, as with pattern-making, and for similar reasons, it has not been thought necessary or desirable to do more than touch on it in this book.

Moulds for Castings. These may be divided into two groups:

1. Green-sand, dry-sand, and loam moulds.
2. Permanent moulds.

The former produce only a single casting per mould and are destroyed partly by the pouring of the molten metal into them and partly in the removal of the casting after it has solidified. Thus each casting requires its own mould. The main difference between a green-sand and a dry-sand mould is that in the former the sand is more or less in its natural or "green" state, whereas the dry-sand mould is dried out before the metal

is poured in. The adjective " green " has no reference to the colour of the sand, which may range from yellow through red and brown to black. Both kinds of mould are made up in the manners described below ; loam moulds are quite different and are considered subsequently.

Permanent moulds are usually made of metal and can be used over and over again so that the one mould may produce many thousands of castings before it is worn out and has to be scrapped. At the present time, however, the use of permanent moulds is almost entirely confined to the production of castings in zinc-base, aluminium, and brass alloys, although one or two foundries do use them successfully for iron castings. Castings produced in permanent moulds are called *die-castings* and the process will be considered later on.

Sand Moulds. The simplest sand mould is merely a depression formed in the surface of a level bed of suitable sand and into which the molten metal is poured and allowed to settle. Such moulds are known as *open sand moulds* ; they are used only for very simple castings and need not be further considered. The majority of sand moulds are made in two parts in wooden, cast-iron, or pressed steel *moulding boxes* or *flasks*. Several types of moulding box are shown in Fig. 26. The boxes are generally used in pairs, one for the bottom part of the mould and one for the top ; the two parts must be registered relatively one to the other and must be securely fastened together when the metal is poured in. Registration and fixing together of the boxes is done by making them with lugs and pins as shown in Fig. 27. Unless the pins fit the holes fairly closely the registration of the boxes may not be very good and when close-fitting pins are used they are sometimes difficult to engage, particularly when the boxes become distorted through use. These difficulties are largely avoided in the design shown in Fig. 28 which has been patented (see *Proc. I.A.E.*, Vol. XXX, p. 539). To register the boxes short, ball-ended pins, A and

FIG. 26.

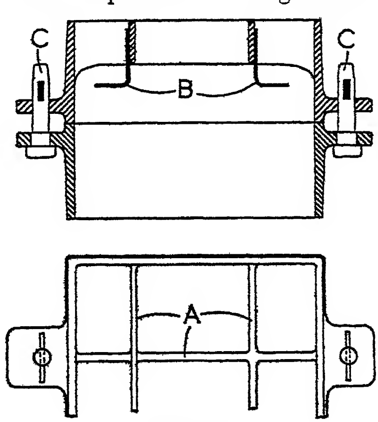


FIG. 27.

B, are provided; one of the ball ends engages a cylindrical hole, fitted with a hardened bush, and the other engages a slot fitted with a hardened liner. The slot allows for distortion of the box so that this does not upset the registration. To guide the top box, while it is being put on and lifted off, longer parallel pins CC are provided, but these are comparatively free in the holes of the top box and are not relied on for registration; the pins CC take the cotters for fixing the boxes together. Large moulding boxes are made with ribs or webs (A, Fig. 27) against which bent rods B, called *gaggers*, may be placed in order to help support the sand rammed into the box. The ends of gaggers should not project above the edges of the ribs or there is a great danger that they may be struck during the ramming, with consequent damage to the mould.

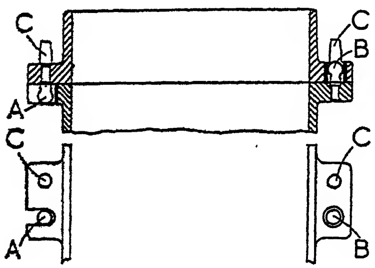


FIG. 28.

A Simple Two-part Mould. The simple mould shown in Fig. 29 consists of a bottom box A, called the *drag*, which has the whole of the cavity of the mould formed in the upper surface of the sand it contains, and a top box, called the *cope*, which merely forms the cover to close the mould formed in the drag. The cope has openings C and D formed in it; the former is where the metal is poured in and is called the *runner* or *sprue* and the latter is called the *riser*. The riser serves to allow the air inside the mould to escape and also to give warning of the filling of the mould, pouring being stopped when the metal is seen to rise to the top of the riser. Risers may be used for another reason which will be considered later and may also be called *headers*. Several runners and headers or risers may be used in a large or complicated mould. The runner may sometimes lead directly into the cavity of the mould but more often is connected thereto by a short passage E called the *gate*. The making up of this mould will now be considered. The drag is made first by taking the pattern and placing it upside down, i.e. with the surface FF downwards, on either a level part of the foundry floor or on a special board called a *turn-over board*, putting a moulding box round it, and ramming sand tightly round it until the box is full. The surface of the sand is then struck off level with the uppermost edges of the box

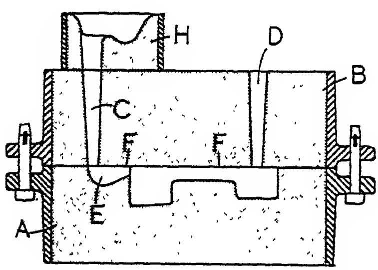


FIG. 29.

by working a straight metal bar across it and the box, together with the turn-over board if one is used, is then picked up and turned over so that the pattern, which is still embedded in the sand, is uppermost. The top surface of the drag is then dusted with *parting sand.* This is sand which, through being burnt, lacks the property of cohesiveness and which will prevent the sand subsequently put into the top box from adhering to that in the drag. Special parting materials are sometimes used; for example, a mixture of tripoli and tallow. (This dusting operation is always necessary although in subsequent descriptions it may not be mentioned explicitly.) The top box, or cope, is next placed in position and fastened by means of the cotters. Conical wooden plugs are then placed so as to form the runners and risers and the cope is rammed up with sand. The upper surface is struck off level, the runner and riser plugs are removed, the cotter pins are withdrawn, and the cope is carefully lifted off. A metal spike is now lightly tapped into the pattern and is struck or *rapped* lightly all round so as to loosen the pattern in the sand of the drag. (This rapping is also always necessary, though it may not always be mentioned explicitly in subsequent descriptions.) The sand next to the pattern may then be moistened slightly with water put on with a brush and the pattern lifted or drawn out of the sand. This is done by means of the rapping spike or by a special handle that is screwed into a bush provided in the pattern. *Nails* or *sprigs* are sometimes inserted into weak parts of the mould. Any damage that may have been done to the surface of the mould during the drawing of the pattern is now repaired, and the channel E is cut. The surface of the mould may now be painted or sprayed with a *claywater solution* or a *blackwash*, the cope replaced, and the cotter pins inserted. The mould is now ready for pouring, but a heavy weight or weights may first be placed on the top of the cope to prevent the pressure exerted by the head of molten metal from lifting the sand, and a *feeding gate*, *pouring basin* or *cup* H may be put on to assist in the pouring of the metal. A piece of perforated zinc is often placed on top of the runner to hold back the metal for a moment.

The parting surface between the top and bottom boxes must always be made to coincide with the largest cross-section of the object in the direction perpendicular to that in which the pattern is drawn, in order that the pattern may be withdrawn from the sand. With most objects, therefore, the mould must be formed partly in the drag and partly in the cope and with many objects a curved or non-planar parting surface will have to be used as shown in Fig. 30. The parting surfaces must, however, always be brought flush with the edges of the boxes all round, as shown in

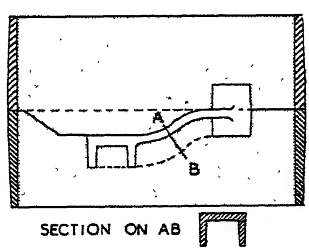


FIG. 30.

the figure. In these cases the making up of the drag may be somewhat awkward and several methods are used to circumvent the difficulties that arise. Three of these methods are illustrated in Fig. 31. The first is to cut away the sand of the foundry floor until the pattern can be placed with the parting line lying in the plane of the floor, the drag being then placed round it and rammed up as usual. The second method is to use a split pattern, the split being along the parting surface. One half of the pattern is placed, flat side downwards, on the turnover board, the drag is put on and rammed up, and the turnover board and box are turned over. The top box is then put on, the other half of the pattern is placed in position, and the mould completed as usual. The half pattern is sometimes made integral with the turnover board. These two methods are not usually practicable unless the parting surface is a plane. The third method, which is commonly used when a fairly large number of castings is required off the same pattern, is to use an *oddside.*

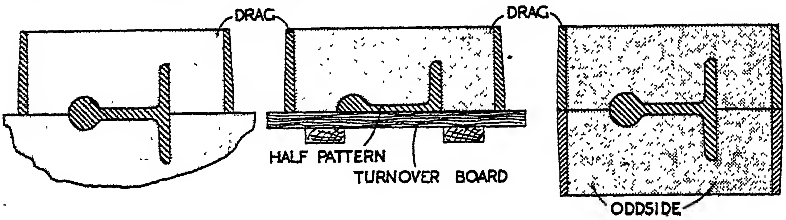


FIG. 31.

This is an additional top moulding box which has been rammed up so that the top surface of the sand is recessed to take the pattern with the parting line level with the top of the box. The pattern is placed on the oddside and the drag of the mould being made is put on it and is rammed up. The drag is then lifted and turned over, the cope is put on it and is rammed up, and the mould completed as usual. The method is similar to the first method except that the sand on which the pattern is laid when the drag is being made is contained in a moulding box instead of being part of the foundry floor. The oddside has the advantage that a binding material may be mixed with the sand of which it is made so as to harden it and thus give it greater permanence ; it may also be made of plaster of Paris or of wood.

The Moulding of Complicated Castings. Castings which are hollow, or whose shape is complicated, often call for more elaborate moulding methods than the simple process described above. Amongst these methods are the use of (1) Cores ; (2) Moulds made in several, instead of only two, parts ; (3) Loose pieces on patterns ; and (4) Drawbacks. These will now be considered.

Cores. Consider the object shown in Fig. 32, the inside shape of which is indicated by the dotted lines. This would be most easily

moulded on its end, with the parting line running down the centre line PP, and the inside shape would be formed by a core. The pattern would be made as shown in Fig. 33, with projecting portions A, B, and C, called *core prints*, integral with it. The mould, shown assembled in Fig. 34, is made up by the usual methods and, when the cope has been rammed up and lifted, the pattern withdrawn, and any patching necessary has been done, a core of sand, whose shape is equal to that of the inside of the object plus the core prints, is placed in the drag. The cope is then replaced and the mould completed ready for pouring. When the mould is poured the metal fills only the space between the core and the inside of the mould. After the casting has cooled and has been knocked out of the mould the core has to be knocked out of the inside of the casting. Great care has to be exercised in placing the core in the mould and it must be held securely between the drag and cope, because if it is improperly placed, or if it moves after the cope has been put on, then the casting will be unduly thin in some places and unduly thick in others and may be unserviceable. Cores are commonly prevented from sagging, or from lifting when the metal is poured, by *chaplets* or *studs* inserted between them and the body of the mould.

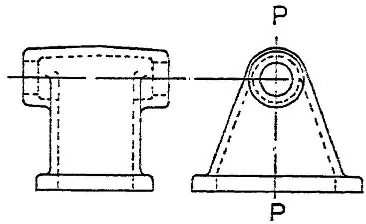


FIG. 32.

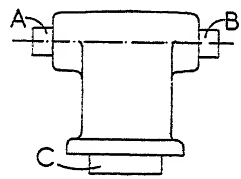


FIG. 33.

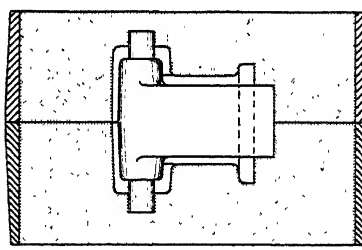


FIG. 34.

Core Boxes. The core itself is made in a wooden or metal mould called a *core-box*, that for the example considered being shown in Fig. 35. It is made in two parts dowelled together so that one half is registered relative to the other half, and the shape of the core is formed as a recess in each half of the box. The core is made by filling the core-box with suitable sand and ramming it up as for a mould; simple clamps are used to hold the halves of the box together during the ramming. One half of the box is then lifted off so that the core can be re-

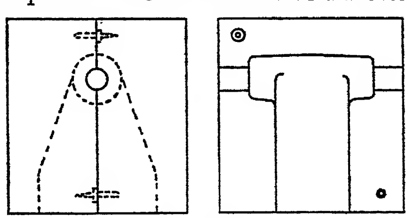


FIG. 35.

moved. For this to be possible it is necessary for the dividing surface of the box to coincide with the largest section of the core; with complicated cores a box made in several parts and with loose pieces may be required, in order to permit withdrawal of the core, or a core made in several parts may have to be used. The materials used for cores will be considered subsequently, but it may be noted that cores usually are lacking in strength until they have been baked in an oven and they may consequently have to be supported on a metal plate or support, similar in shape to one half of the core-box, until the baking operation has been done. Wires and rods are also used inside cores to help strengthen them, these rods being put in during the ramming.

Three-part Moulds. It has been stated that the parting surface of a two-part mould must coincide with the largest cross-section of the pattern and this often necessitates the use of a non-planar or of a curved parting surface. With many castings it will be impossible, however, to use a simple mould made in only two parts and a mould made in three or more parts may be necessary. An example of a three-part mould is given in Fig. 37 and the method of making it will now be described. The casting, an isometric view of which is given in Fig. 36, is actually hollow but for simplicity the cavity will be ignored and the casting will be regarded as being solid.

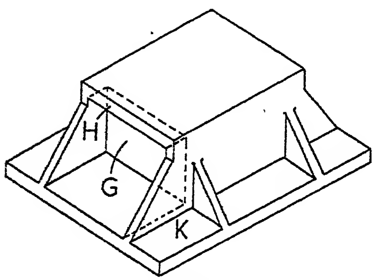


Fig. 36.

The pattern, which is shown in the mould, is made in two parts, 1 and 2, the division being along the surface seen as AB. After the drag, which in this example is a very simple one, has been rammed up and turned over, the pattern is put into place and the middle box (called the *cheek*) is put on and rammed up. Unless the middle box is equal in depth to the pattern the parting surface at the top will have to be formed as shown by the lines CDEF, sloping from the edges of the box down to the level of the top surface of the pattern. The top box is then put on and rammed up, the runner and riser plugs being put in as usual. The top box is then lifted and the part 2 of the pattern is drawn. This enables the middle box to be

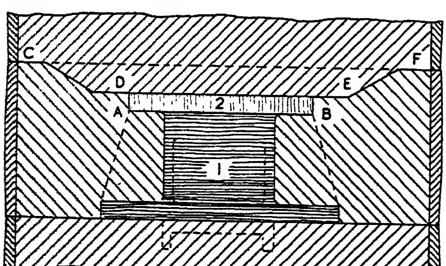


Fig. 37.

lifted and the other part of the pattern to be drawn. The boxes are then re-assembled to complete the mould. If the bottom of the casting had been irregular in shape as indicated by the dotted lines then the pattern might sometimes be made in three pieces, the portion lying in the drag being separate so as to facilitate the moulding of the drag. It may be noted that if the recesses in the ends of the casting had been avoided by making the surfaces G flush with the ends H of the top, then the moulding could have been done in a two-part mould.

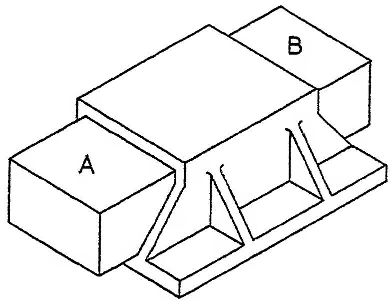


FIG. 38.

An alternative method of moulding the above casting in a two-part mould is to use cores to form the recesses in the ends. The pattern would then be as shown in Fig. 38 where A and B are the core prints. The mould is shown in Fig. 39. The use of external cores in this manner is very common and often a necessity, no alternative moulding method being possible, but even when an alternative method is available the use of cores would generally be preferred if any considerable quantity of castings was required because the mould could be made more quickly and hence more cheaply.

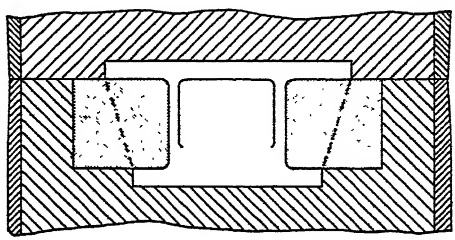


FIG. 39.

The Use of Loose Pieces. This method would enable the casting shown in Fig. 36 to be moulded in a two-part box as will be seen from Fig. 40 which shows the pattern in the mould. The flange portions at the top of the recesses in the ends of the casting are now made separate from the body of the pattern; these loose pieces are seen at L and M, the casting being moulded upside down. The mould is made by placing the pattern, with the surface N downwards, on a turnover board, the drag being rammed up as usual. After the cope has been rammed up

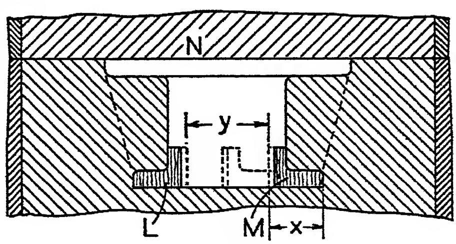


FIG. 40.

and lifted the body of the pattern can be drawn, leaving the loose pieces behind. Those pieces can then be withdrawn sideways, one at a time, as indicated for the piece M by the dotted outline, until they are clear and can be lifted out. For this to be possible the width y of the space left by the body of the pattern must be greater than the width x of the loose pieces.

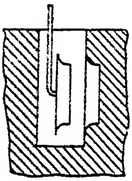


Fig. 41.

The bosses placed on flanges where bolt holes are situated have frequently to be made as loose pieces which are left behind when the pattern is drawn and are subsequently fished out with the aid of a bent piece of wire as is indicated in Fig. 41. In these cases the loose piece is often secured to the pattern by a pin that is withdrawn when sufficient sand has been rammed round the piece to keep it in place while the ramming is completed. Small loose pieces are best avoided if possible, because they not only make the moulding somewhat more difficult but are apt to get lost and so cause trouble; they can sometimes be avoided by carrying bosses into the adjacent wall of the casting as indicated in Fig. 42.

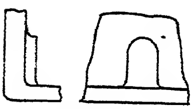


Fig. 42.

Drawbacks. A drawback is a body of sand that is used instead of an external core in order to facilitate the moulding of undercut parts of castings. Since moulding sand is comparatively weak, drawbacks have to be provided with lifting plates by means of which they can be lifted out of the mould when necessary; they are invariably placed in the drag. An example is shown in Fig. 43. The drag is rammed up and turned over as usual and the sand that occupies the space which will eventually be filled by the drawback is cut away. After dusting the surface with parting sand the lifting plate and rod or rods are put in position and sand is again rammed in. The eye of the lifting rod is situated in the sand of the drawback just below its upper surface. After the cope has been rammed up and lifted the drawback may be lifted out; the pattern can then be withdrawn. The drawback is then replaced and the cope put on to complete the mould. In the example the face xy of the drawback must either be parallel to the side ab of the pattern or, preferably, be inclined at a smaller angle to the horizontal, otherwise it will not be possible to lift the drawback out.

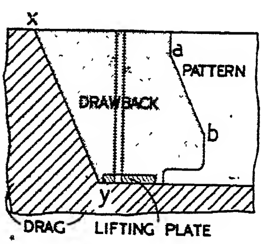


Fig. 43.

False Cores. The use of a three-part mould, or of a core produced in a core-box, may sometimes be avoided by using what is called a *false*

core as shown in Figs. 44 and 45, which shows a mould for a pulley with a curved rim. The false core A is made in green-sand and is a ring of sand of the section shown shaded. Since green-sand has little strength the green-sand core must always be supported during the making up of the mould, and the procedure is as follows. The bottom half-pattern is put on a turnover board upside down, and the drag rammed up and

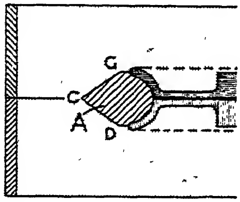


FIG. 44.

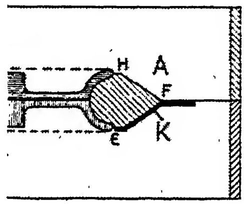


FIG. 45.

turned over as usual. The upper face of the drag is then cut away to the parting line CDEF and is dusted with parting sand. The top half of the pattern having been placed in position sand is rammed in to form the false core and is cut away to form the parting line CGHF. After dusting with parting sand the top box is put on and rammed up. The top box is then lifted and the top half of the pattern is drawn. The top box is then replaced, the complete mould is turned over, and the drag, which is now on top, is lifted. The bottom half of the pattern, now on top, is then drawn, the drag is replaced, and the whole mould turned over and made ready for pouring. The time taken by the above procedure can be reduced by using a lifting ring or plate K (Fig. 45) for lifting the false core. This plate is put in after the drag has been rammed up and turned over and the parting surface has been formed, the false core being rammed up on top of it. After the cope has been lifted and the top half of the pattern drawn the false core can be lifted, on its plate by screwing rods into holes provided in the plate, and the bottom half of the pattern can then be drawn. The false core is then replaced and the cope put on to complete the mould. If any considerable quantity of these castings was required a core-box would generally be made and ordinary cores used. The pattern would then be made solid and would include a core print corresponding to the shaded section A in Fig. 44.

Marking and Colouring of Patterns. The British Standards Institution have issued a specification (No. 467—1932) dealing with this matter. For iron and steel castings the pattern body is coloured black and the *ends* of core prints red. For non-ferrous castings the pattern body is made red and the *ends* of core prints black. The peripheries of the core prints are made the same colour as the ends if the cored hole is to be unmachined and are coloured yellow if the hole is to be machined.

The seats of all loose pieces and the backs of the loose pieces themselves are left natural colour and varnished.

Moulding Sands. A satisfactory moulding sand must possess

1. *Cohesiveness*, or the ability to retain its shape after the pattern has been removed and during the pouring and solidification of the metal.
2. *Refractoriness*, so that it can withstand the heat of the molten metal without fusing.
3. *Permeability*, which means that the grains of sand must be porous so as to allow the gases evolved during the pouring of the metal to escape.

The mould as a whole must also be porous, that is, the grains of sand must not be packed too closely together and spaces must exist between them. The porosity of a mould thus depends largely on the degree of ramming and this is a matter on which the moulder has to exercise skill acquired by experience. The adequate venting of a mould, however, generally requires the provision of venting channels and these are formed by pricking the sand of the cope with a wire after it has been rammed up, thus forming a number of small holes or vents. The pricker is not carried quite down to the surface of the pattern. Cores also require careful venting and channels are sometimes formed in them by putting in a length of wax " wire " during the ramming ; this melts out during the baking of the core, thus leaving the required vent. This vent is carried through to the prints of the core and extra venting to the surrounding parts of the mould is arranged.

Cohesiveness or bonding property is imparted to moulding sands chiefly by the presence of from 2 to 6 per cent of clay, although hydrated iron oxide which is sometimes present in natural sands, also assists. The necessary clay may be present in the sand when it is dug out of the pit, the sand being then a *natural* moulding sand, but it is becoming more and more common to add colloidal clay to a washed sand in the proper proportions to give the required cohesiveness. Moulding sands made up in this way are called *synthetic* sands. Both natural and synthetic sands must contain moisture, normally up to about 8 per cent, and, when ready for use, must be free from lumps and foreign matter. The sands used for iron castings also commonly have about 8 per cent of coal dust mixed with them. The gases produced by the hot metal coming into contact with the coal dust form a " blanket " which protects the surface of the mould and prevents fusing of the sand grains, thus helping to produce a good surface finish or skin on the casting. The clay in a moulding sand is ideally distributed in the form of a thin layer on the individual grains and this distribution and the complete mixing of the water and coal dust additions is brought about by milling the sand

mixture in various types of mill. The sand is finally *riddled* by passing it through sieves.

Bentonite, which is a colloidal clay of volcanic origin, has been found to be superior to ordinary colloidal clay in imparting cohesiveness to moulding sands and its use, either instead of or in addition to ordinary colloidal clay, is becoming widespread. *Fuller's earth* is also widely used to increase the bonding properties of moulding sand.

The bonding strength and permeability of a moulding sand may be measured by means of suitable testing methods which have now become more or less standardised in most countries. Considerable research work is being done at the present time on the properties of moulding sands. The size and sharpness of the sand grains are of importance. Thus seashore sand, whose grains are rounded, is unsuitable as a moulding sand. In general a sand of smaller grain size is used for brass castings than for iron castings because brass has an intense " searching " action and tends to penetrate between the sand grains.

Core Sands. Cores are made either from ordinary moulding sand to which additional binding material has been added or from a sand that is free from clay (seashore sand is often used) the bonding being provided by the addition of *binders*. The latter may be divided into three groups : (1) *Water soluble binders ;* (2) *Oil binders ;* and (3) *Pitch and resin binders*. In the first group the commonly used materials are molasses and wood extract concentrates ; wheat, rye, and barley flours ; dextrin and glutin ; these are used with ordinary moulding sand. In the second group are linseed oil, soya-bean oil, chinawood oil, and fish oils ; these being used with seashore or similar clay-free sands. Some of these materials leave a carbon deposit on the grains of sand after subjection to the heat of the molten metal and this deposit greatly impairs the bond given by subsequent additions of binder, consequently core sands are frequently used only once. The strength of bond imparted by core binders is not developed until the cores have been dried in ovens, and so while cores are in the " green " state they generally have to be supported so as to prevent them from sagging. For this purpose, as has been already mentioned, core supports, roughly similar to one half of the core-box used to make the core, are used. The drying of oil sand cores is done at temperatures of about 200° C., temperatures lower than about 175° C. resulting in prolonged drying periods and temperatures above about 250° C. in the weakening of the bond. Cores made with water-soluble binders are dried at lower temperatures, usually about 175° C. It has been found that the green strength of cores can be improved by using a sand composed of grains of differing size instead of one composed of grains of uniform size. With all cores it is necessary that the strength of bond should be maintained until the metal has solidified but that the bond shall be destroyed by the time the casting is knocked out of the mould, otherwise difficulty will be experienced in getting the cores out of the castings.

Dry-Sand Moulds. These are made in the same manner as green-sand moulds but are dried out before the metal is poured in. The drying may be more or less superficial, being done by braziers placed inside the moulds or by gas torches, which gives *skin-dried* moulds, or the moulds may be dried in an oven. Dry-sand moulds are stronger and more porous than green-sand moulds, the increased porosity being largely due to expansion of the sand grains, and they are commonly used for steel and for large copper-alloy castings ; for the former because they stand up better to the higher temperature and greater scouring action of the metal during pouring, and for the latter because of the searching action of those alloys. Green-sand moulds are, however, sometimes used for steel castings in preference to dry-sand moulds because they offer less restriction to the contraction of the casting during cooling, which is one of the common troubles experienced in casting steel, which has a much higher coefficient of expansion than cast iron.

Loam Moulds. These are made in an entirely different manner from sand moulds and are used principally for large castings. Loam is a mixture of sand and clay but additional materials of an organic nature, such as chopped hay, sawdust, and cow-hair are introduced, partly to increase the bonding properties and partly to give porosity. The mould is made up as follows. A brick structure is built up, usually on the floor of a pit in the foundry floor, loam being used as mortar and ample spaces being left between the bricks, so as to form a foundation for the core of the mould. This brickwork is then plastered with a layer of loam and is shaped by means of a strickle-board, carried on a central pivot about which it can be swung. When the loam has dried on the core structure, drying being hastened by means of braziers placed inside the structure, it is blackwashed. Another layer of loam, called the " thickness," is then plastered on and is shaped to the outside shape of the object by means of a second strickle-board, called the " thickness board." This layer is also allowed to dry and is blackwashed. A thick layer of loam is then put on and a brick structure is bedded down on to this layer, a lifting plate or ring being put at the bottom and a runner being formed at the top. When this loam has dried out the whole of the cope structure is lifted off and the thickness layer of loam is cut off the core. After any patching that may be necessary has been done the core and cope are again blackwashed and, after drying, the cope structure is replaced on the core and the mould is ready for pouring. The process is obviously applicable principally to objects whose inside and outside shapes are surfaces of revolution. Details and parts which cannot be moulded by means of a strickle-board may be formed by sand moulds made in boxes and incorporated into the loam mould structure. The core and cope structures may also be swept up separately instead of using a " thickness " as described above.

The Randupson Process. In this process, which was developed in France, moulds are made of a cement-sand mixture to which water is added, the mixture ultimately having a consistency and texture rather like that of the oil-sand mixtures used for cores. The sand is a silica sand and the mixture is pushed, rather than rammed, round the pattern. Natural drying is used and takes from 48 hours with small moulds up to 72 hours with large ones. The moulds are blacked after drying ; they are made in wooden boxes with a pronounced draft or taper and can be removed from the boxes before drying is completed, thus reducing the number of boxes that must be provided. The halves of the mould are held together by a number of clamps applied round the edges and weights may be placed on the top of the mould to prevent it lifting. When this process is used the half patterns are sometimes mounted on a board which is integral with the sides of the moulding box. The patterns are then similar to the plate patterns used with moulding machines (see p. 86). The chief advantage claimed for the process is that, owing to the fact that the moulds can be poured at a higher temperature than is feasible with ordinary green-sand moulds, castings of higher quality are produced. The sand from used moulds is reconditioned for further use, the cement being eliminated. The process is used, at present, by only a few foundries.

Centrifugal Casting. In this process, which is extensively used for the manufacture of cast-iron pipes and the " pots " from which piston rings are turned, the mould is carried in a chuck so that it can be rotated about its axis at a speed of several hundred revolutions per minute. Whilst the mould is rotating, molten metal is poured in through some form of spout which distributes it along the length of the mould. Centrifugal force keeps the molten metal out against the inside of the mould and makes the thickness uniform. When the metal has solidified, the mould is brought to rest and the casting is drawn out. The process is essentially one adapted to produce objects which are surfaces of revolution. In recent years steel has been successfully cast centrifugally ; the moulds in one example were made of a low carbon, chromium-molybdenum steel and rotated at about 350 r.p.m. The steel being cast had the composition carbon 0·35–0·4, manganese 0·65–0·8, silicon 0·3 max., chromium 0·9–1·1, copper 0·5–1·5. It was melted in a 4-ton electric furnace and transferred direct to the moulds. Solidification took about 3 minutes. The castings were subsequently normalised.

Malleable Castings. These are castings whose composition and structure have been changed by suitable heat treatment so as to make the iron more like wrought iron and consequently to increase its ultimate strength and percentage elongation. The untreated castings have to be cast in metal that will give white cast iron, and as this metal lacks fluidity that property has to be restored by the inclusion of comparatively high

phosphorus contents ; sulphur is also generally rather high and, in consequence, the silicon content is high too. Two processes are used to malleabilise the white iron castings and these are known by the names *Whiteheart* and *Blackheart* processes because they give castings which when fractured have relatively white or black appearances. The whiteheart process, which is used chiefly in England consists in packing the castings in hæmatite ore in boxes and heating them to between 800° and 950° C. for periods ranging up to 10 days and then cooling them down very slowly. Some of the carbon in the casting is oxidised and a ferritic structure is thus obtained in thin sections, while in thicker sections the structure is graded from a ferritic one to one composed of ferrite and pearlite with nodules or rosettes of graphite dispersed throughout. In the blackheart process, which is used chiefly in the U.S.A., the castings are again heated in boxes but the packing material is neutral and the temperatures used are somewhat lower, ranging from 700° to 850° C. The carbon is not reduced in amount but the cementite is broken down into ferrite and carbon and the latter is collected into nodules dispersed throughout the mass.

The ultimate strength of malleable castings ranges from 10 to 25 tons per sq. in. and the percentage elongation from 10 to 15.

Steel Castings. In general principle the production of steel castings is similar to that of iron castings but in practice steel founding is much more difficult, and is consequently much more specialised, than iron founding. The chief difficulties are due first to the higher melting point of steel which makes it more difficult to get moulding sands that will stand up to the high temperatures involved, and, secondly, to the greater contraction of steel castings in cooling which greatly increases the danger of cracks being formed during cooling. Also steel, unlike cast iron, does not expand on solidification and so the production of clean, sharp castings is not so easy. Small castings are produced in moulds made of ordinary moulding sands, but larger castings are generally produced in " compos " moulds. Compos is a mixture of old crucible pots, old firebricks, and Sheffield gannister all milled up together with fireclay and some carbonaceous material such as coke or graphite. The moulds, when made, are painted with mould paints consisting largely of silica flour and are smoke-blackened. It is frequently necessary to break down the mould almost immediately solidification has occurred in order to leave the casting free to contract, also cores must not be too rigid or they will cause trouble. To avoid cracking troubles during cooling, steel castings are provided with numerous webs joining the flanges and the walls ; these webs solidify fairly early on and then take some of the stresses set up during cooling. The provision of webs can, however, be overdone, with results just the opposite to those intended. Steel castings are almost always given a heat treatment after being knocked out of the

mould ; this treatment is often extensive and with large castings may occupy several weeks. It is most important with steel castings to keep the section thickness as uniform as possible.

Defects in Castings. The principal defects met in castings are: (1) Scabs ; (2) Blowholes ; (3) Hard spots ; (4) Porosity and Sponginess ; (5) " Cold shuts " ; (6) Displaced cores ; (7) Fins ; and 8) Cracks. Scabs are due to portions of the sand forming the surface (of the mould being detached or broken away so that an excrescence is left on the surface of the casting. They may be due to faulty ramming, incorrect placing of gates, or the use of inferior sand. Blowholes are commonly due to insufficient venting of the mould because of too severe ramming or the lack of risers ; they may be caused by the moisture content of the sand being too high or to faulty composition of the metal itself. Pouring the metal at too low a temperature is another cause. Hard spots are generally due to too rapid cooling of the metal in conjunction with unsuitable composition and will occur chiefly in the thin sections. The benefit obtained in this respect from the use of nickel has already been mentioned. Porosity, which means that fluids will percolate through the metal although no holes are visible even under magnification, is generally due to incorrect composition of the metal, too high a percentage of phosphorus being one cause ; it may also be due to the inclusion of dirt in the metal during pouring. Sponginess occurs mostly in the heavy sections of castings and is generally due to lack of sufficient headers to feed the section during solidification of the metal. " Cold shuts " are discontinuities produced by too slow pouring of the metal or by pouring at too low a temperature, the thin sections freezing before the mould is properly filled, or by the meeting of two streams of metal which are not hot enough to unite. Displaced cores are not uncommon and may lead to rejection of a casting because the metal at one side becomes too thin to be properly machined. In large production foundries elaborate gauges are used to check the setting of cores in the mould in order to obviate this trouble. Fins are due to the parts of the mould not fitting properly, to core prints being slack in the mould, and to cracks occurring in the drying of cores. Cracks in castings may be due to faulty design, which makes no provision for the contraction of the casting during cooling, to too high a pouring temperature, or to too hard and rigid a mould.

Fettling. After being knocked out of the moulds castings go to the fettling shop where the runners and risers are cut off and the castings are cleaned up by means of chisels, grinding wheels, and shot-blasting. The latter consists of projecting quantities of steel shot on to the casting by means of a blast of compressed air, thus effectively cleaning the casting. The castings may also be Brinell tested to ensure that they are not too hard to be machined and, where pressure tightness is important, may be tested under water pressure for porosity. They may also be inspected

by means of limit gauges to ensure that they conform to the specification laid down and to ensure that they will fit the machining jigs and fixtures during their early stages in the machine shops.

Mechanical Aids in Moulding. The most important mechanical appliances used to reduce the time and cost of making moulds are: (1) *Sand slingers*, and (2) *Moulding machines*. A sand slinger consists essentially of a rotating impeller whose blades are arranged to impel or sling a succession of "lumps" of sand into the moulding box with sufficient force to pack it to the required degree and thus to eliminate, or at least greatly reduce, the hand ramming that has to be done. The impeller head can be moved about so as to direct the sand into all parts of the mould and the sand is brought to the impeller from a hopper by a belt conveyor. Sand slingers are used chiefly with large moulds and with moulds that cannot be handled easily on moulding machines; they are built in three forms: (*a*) Portable, on a wheeled carriage that can be moved to any part of the foundry; (*b*) Semi-portable, on a carriage that travels up and down a rail track; and (*c*) Fixed, the impeller head being on the end of a swivelling arm carried on part of the foundry structure.

Moulding machines are built in a wide variety of forms, ranging from small hand-operated machines for simple moulds up to large power-operated machines capable of handling moulding boxes up to 6 ft. square. The simplest machines merely draw the pattern from the mould, the ramming being done by hand, while the larger machines ram the sand as well as doing the rapping and stripping of the pattern from the mould. Some machines also turn the mould over right side up ready for patching and delivery to a conveyor. *Plate patterns* are almost universally used with these machines, the pattern being either fixed to or made integral with a plate that is approximately the size of the moulding box being used and which is secured to the table of the machine. The latter is provided with pins to locate and secure the moulding box. Except for simple objects that can be moulded entirely in the drag two pattern plates must be used, one for the drag and one for the cope; the two plates are used concurrently in two machines. Fig. 46 shows a typical plate pattern in position on a moulding machine while a second example is seen lying on top of the moulding boxes in the middle of the illustration. On the left a rammed up box is seen in position on the machine; it is ready to be lifted off, the pattern plate having been withdrawn downwards. This particular machine only draws the pattern; the ramming has to be done by hand. Two methods of ramming the sand are used in moulding machines, one is called *jolting* and the other *squeezing*, whilst some machines employ a combination of both methods. Whichever method is used the table that carries the plate pattern is arranged to be lifted up by mechanical, compressed air, hydraulic, or electro-magnetic means. In jolt-ramming after the table has been raised a few inches it is allowed to

drop freely back against the frame of the machine and the inertia of the sand in the moulding box packs it round the pattern and in the box. This method of ramming tends to produce a mould in which the sand next to the pattern is the most tightly packed and the density of packing decreases as the distance from the pattern increases, and this is not suitable for many moulds. In the squeezing method of ramming the raising of the moulding machine table brings the sand in the moulding box up against a fixed head, carried on part of the frame of the machine, and the sand is then squeezed by a steady pressure applied to the piston raising the table. This method of ramming tends to produce a mould in which the most densely packed sand is at the top of the mould (as it lies in the machine) and this is not the ideal form. A combination of the two

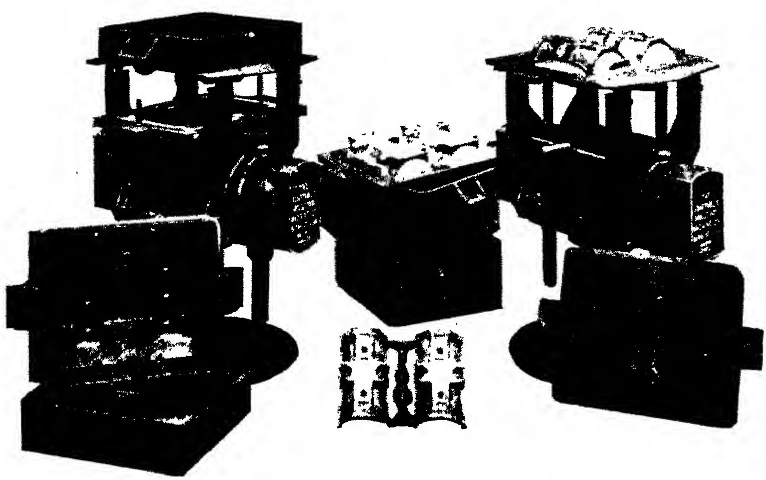


FIG. 46.

methods gives better results than either method used alone and is consequently often used. When this is done the jolting comes first and the squeezing second. Two methods of drawing the pattern from the mould are used in moulding machines; in one the pattern plate is held fixed and the moulding box is lifted upwards, while in the other method the exact opposite is done. Occasionally a *stripping plate* is used; this is a plate equal in dimensions to the moulding box and which has been cut away round the outline of the pattern. The stripping plate lies on top of the pattern plate and supports the sand in the mould while the pattern is being drawn away from the sand.

An example of a squeeze-strip type of moulding machine is shown in Fig. 47. It is manufactured by British Insulated Cables, Ltd., and is electrically operated. The plate pattern is seen in position and is carried on a stool fixed to the head of a ram, the lower part of which is surrounded

by a solenoid winding. When this winding is energised the ram and pattern plate are raised up, together with the stripping frame, which surrounds the pattern plate, and the moulding box, which is carried by the stripping frame. The sand in the moulding box is thereby squeezed against the pressure head carried by the overarm. When the solenoid current is switched off the ram and pattern plate (and also the registering pins, which are carried by the pattern plate and which project through

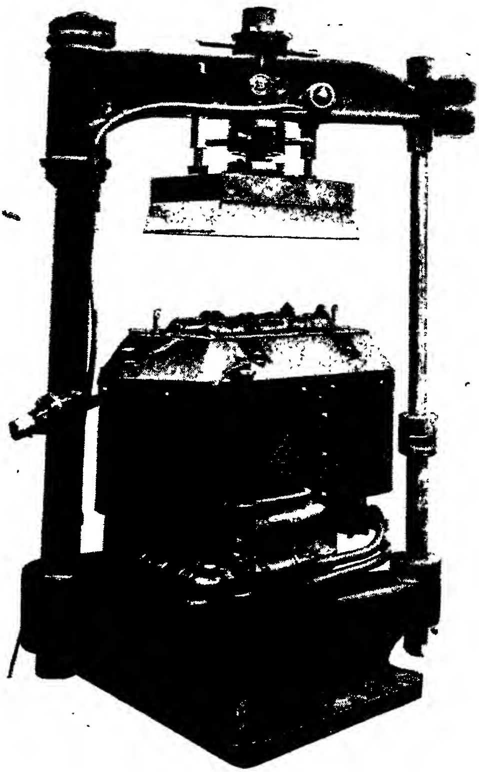


Fig. 47.

holes in the stripping frame) fall quickly back to the bottom position but the stripping frame and mould are held up by dash-pots (the pistons of which are fixed to the stripping frame) until the valve controlling the dash-pots is operated. This valve is seen in the centre of the illustration. The pattern is thereby stripped from the mould. During the stripping operation an electrically operated vibrator (seen on the left) vibrates the stripping frame. When the pattern has been stripped the stripping frame can be lowered so as to permit the pressure head to be swung out of the way and the mpleted comould to be removed. The overarm carrying

the pressure head is braced at its right-hand end by the strain post, the lower end of which engages a recess in the pillar seen projecting upwards from the frame.

A jolt-ram roll-over moulding machine made by Messrs. Macnab & Co. is shown in Fig. 48. On the right is seen the table to which the plate pattern and moulding box are fixed and which rests on the jolting ram during jolting. This is done by raising the ram, by compressed air, and letting it fall back on to the frame of the machine a number of times. After jolting, the surface of the sand is struck off and a bottom board is placed on the top of the moulding box and this board, together with the

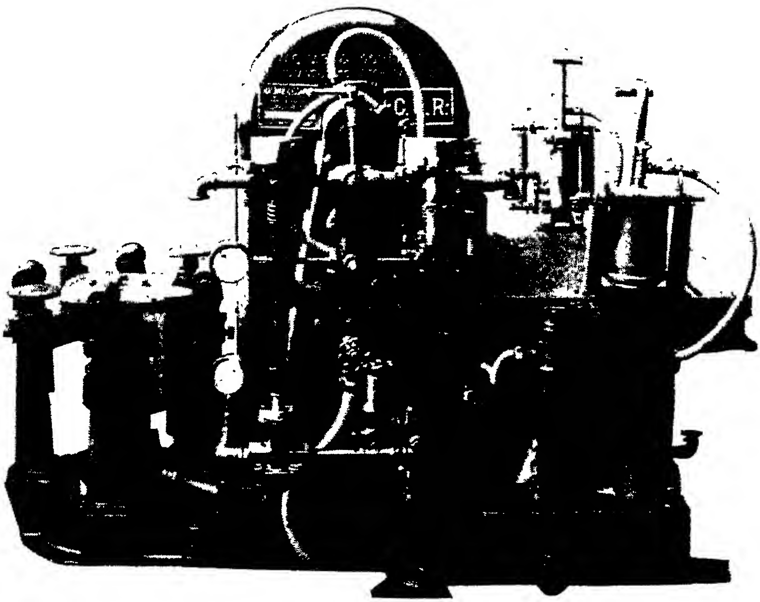


Fig. 48.

moulding box, is clamped to the table by the pneumatic clamps seen at the ends of the table. The latter is also automatically locked to the roll-over arms, the pivot of which can be seen close to the letter C at the top of the frame on the centre line of the machine. These arms are cranked so that their ends lie under the table when the latter is on the jolting ram, but the arms are clear of the table during jolting. The roll-over arms then rotate through 180 degrees thereby inverting the mould and bringing it vertically over the stripping ram seen on the left. During the roll-over a vibrator vibrates the pattern plate. The stripping ram is then raised, pneumatically, until the four supports seen at its corners bear on the bottom board, which is now underneath. The supports are arranged so that they all bear equally on the bottom board. The pneumatic clamps

are then released so that when the stripping ram is lowered the mould is drawn downwards from the pattern plate, which is still fixed to the roll-over arms. The latter are rolled back to the starting position where they are automatically released from the table when the latter is seated on the jolting ram. The stripped mould is lowered until it rests on rollers and can be rolled off for disposal.

Methods of Melting Metals in the Foundry. For cast iron there are three methods, namely, in cupolas, in rotary or oscillating furnaces, and in air furnaces. The last method is used for special purposes such as the production of iron for malleable castings and will not be dealt with. The cupola is the cheapest method except for small quantities, but it cannot be controlled so well as can the rotary furnaces and the latter are consequently widely used for the production of special grades of iron. The general arrangement of a cupola is shown in Fig. 49; it is a

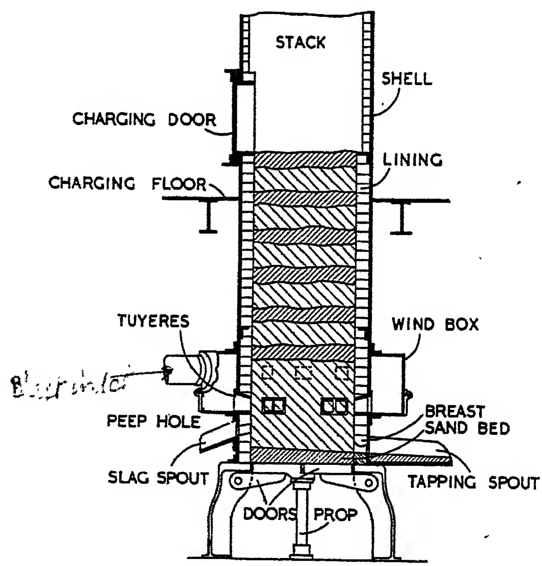


Fig. 49.

cylindrical metal structure lined on the inside with firebrick. At the bottom are doors through which access can be gained to the inside for the purpose of patching the walls when necessary and there is also a hole through which the molten metal produced can be drawn off. At a height of about 20 in. above the bottom of the cupola is a ring of holes called "tuyeres"; these tuyeres are formed in castings that are built into the walls of the structure and at the outside they open into a box, called the "wind box," which is connected by a pipe to some form of blower. At a height of from 12 to 20 ft. above the level of the tuyeres is the charging

door through which the materials comprising the cupola charge are introduced. A platform is arranged at a convenient level for the men who charge the materials and elevators and lifting tackle are usually provided to facilitate this handling. The floor of the cupola is made up, after the doors have been closed and propped, by spreading burnt sand over it, this sand being sloped towards the tap hole as shown. When starting up the cupola a layer of kindling wood is placed on the cupola floor and then coke is charged in until it reaches just above the top of the tuyeres. The kindling wood is then lighted and the natural draught of the stack is relied on to ignite the coke bed. When the latter is thoroughly ignited charges of metal, coke, and sometimes limestone are put in in sequence until the level of the charging doors is reached. The blast is then turned on and, in about 10 minutes or so, molten metal will start to trickle down past the tuyeres and to collect at the bottom. The metal charges consist of pig-iron, steel scrap, and cast-iron scrap, and the usual practice is to put the pig-iron round the outside, in contact with the cupola walls, the steel scrap in the middle, and the cast-iron scrap evenly on top of both. The weight of the coke charges, subsequent to that for the bed, is made sufficient to fill the cupola for a height of about 6 in. The metal charges are from eight to twelves times and, when used, the limestone charges are about one-fifth of the weight of the coke charges. Unless the cupola is going to be operated for long periods the limestone charges may not be necessary. The blower supplying the blast maintains a pressure of from 6 to 24 oz. per sq. in. The molten metal and slag collect at the bottom of the cupola, the slag, being the lighter, floating on the top of the metal. When sufficient metal has been melted to bring the level of the slag to about 4 in. below the bottom of the tuyeres the slag is run off by unplugging the slag spout, which is situated opposite to, but a bit higher than, the tapping hole. In some cupolas two rows of tuyeres are used, one above the other, and several special types of cupola have been developed in recent years. Various forms of blower are used for supplying the blast, but an electrically driven centrifugal type fan seems to be the type most commonly used in modern installations. A medium-sized cupola with an inside diameter of about 3½ ft. takes about 3 hours to get started up and ready to supply metal. It can be kept in operation for a period up to 10 hours or so but must then be closed down, cleaned out, and patched as necessary before being restarted. In small foundries it is fairly common practice to light up the cupola some time in the morning so that moulds can be poured during the day, the cupola being shut down in the evening and the doors opened for cleaning out slag, etc.; the doors are left open during the night and so the cupola lining is cool enough for patching early next morning for the next day. In large foundries several cupolas would be in operation and would be shut down in rotation. Some cupolas are provided with receivers situated adjacent to but below the

tapping hole and into which the metal is run instead of running it direct into shanks or ladles. Additions of alloying materials are sometimes made in the receiver instead of being put in with the metal charges and passing through the cupola.

During its passage through the cupola the metal picks up a certain amount of carbon and sulphur from the coke and loses some silicon. When no steel scrap is used the carbon content of the iron produced will generally range from about 3·4 to 3·8 per cent, but the use of steel scrap enables the carbon content to be brought down to as low as 2·5 per cent. Since the melting point of cast iron rises as the carbon content falls, when steel scrap is used the cupola has to be manipulated so as to produce the necessary increase in temperature. The production of iron per pound of coke used in cupolas ranges from as low as 6 lb. up to as high as 12 lb. This is better than is possible with other methods of melting. Air furnaces, for example, achieve only about 4 lb. of metal per pound of fuel. Rotary furnaces use more expensive fuels than coke and their melting costs are higher than those of the cupola but, as has been mentioned, their great advantage is the facility with which the composition of the metal produced can be controlled.

Melting of Non-Ferrous Metals. The copper alloys and, to some extent, the aluminium alloys, are melted in crucibles that are placed in furnaces fired by coke, gas, or oil. A typical arrangement is shown in Fig. 50. The crucibles are made of plumbago. When coke firing is used contamination of the metal charge by sulphur is sometimes difficult to avoid. When the metal is melted the crucible is lifted out and the metal is poured into a ladle. Tilting furnaces are also commonly used; these are usually gas or oil fired. Aluminium alloys are commonly melted in cast-iron pots heated by gas or oil. Because molten aluminium will dissolve iron precautions have to be taken to prevent contamination and the melting pot has to be painted at frequent intervals, sometimes daily, with a wash composed of whiting, waterglass, and water; this wash is sometimes put on top of a graphite-water wash and effectually prevents absorption of iron by the aluminium. Oxidation of the surface of the charge always occurs to some extent but can be kept within bounds

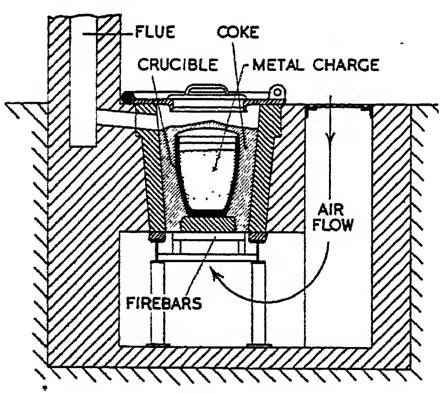


Fig. 50.

by keeping the surface covered with a layer of charcoal. Most molten metals will dissolve gases such as hydrogen and nitrogen and this is a source of trouble in the production of castings; since the quantity of gas absorbed increases with the temperature of the metal the latter should not be heated more than is necessary. Generally speaking stirring of the metal should be avoided as much as possible as it increases both the absorption of gases and oxidation of the metal. Most metals have to be "cleaned" just before pouring into the ladles, by the addition of fluxes. For the production of comparatively small quantities of special alloys high-frequency electric furnaces are often used, since this type of furnace gives a very accurate control of the temperature and also the furnace conditions are such that oxidation and gas absorption are at a minimum.

Die-Castings. These may be divided into (*a*) Gravity die-castings, and (*b*) Pressure die-castings. The former are made by pouring molten metal into moulds which are essentially the same as sand moulds except that they are made in metal, usually cast iron or steel. The parting surface is usually made vertical instead of horizontal, however, as is shown in Fig. 51 which illustrates a simple mould. The shape of the

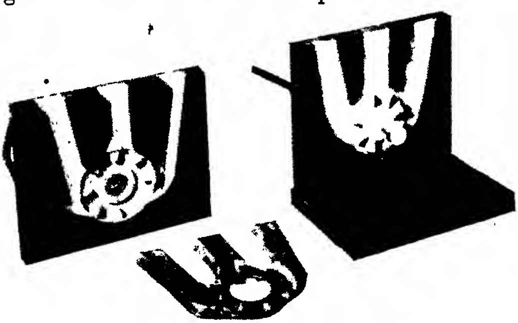


FIG. 51.

object is formed as recesses in the faces of the two dies and the plane dividing them must contain the largest cross-section of the object just as in a sand mould. A runner and risers are arranged as shown and a number of small tapering grooves are cut from the edges of the recesses to the outside edges of the dies for venting purposes. The faces of the dies are painted with a wash similar to that used for the melting pots in which the metal is melted. In use the dies are placed on a metal table and after being heated to a suitable temperature by a gas torch are closed up and secured together, simple latches being provided for this purpose. The metal is then poured in from a ladle until the mould is full, the dies being sometimes tilted at the beginning of the pour and gradually brought horizontal as the metal fills the cavity. When sufficient time has elapsed to permit the metal to solidify the catches are undone and the dies separated so that the casting may be removed. The dies are then closed up again and another casting is poured. The heat

necessary to keep the dies at the proper temperature comes, after the first few castings have been poured, from the molten metal itself, the gas heating being usually required only when starting a run. With small castings it is sometimes difficult to manipulate the dies quickly enough to maintain them at the proper temperature and continuous gas heating may have to be used, while with large castings a pause may have to be made between successive pourings to prevent the mould from overheating. It will sometimes take an operator a day or more to determine the right speed of operation. With complicated objects the dies may have to be made in several parts and many cores may have to be used; in these cases the dies may be very complicated and expensive to make. Cores generally have to be cooled, after each casting is poured, by dipping them in water. The life of the dies, on the other hand, may be

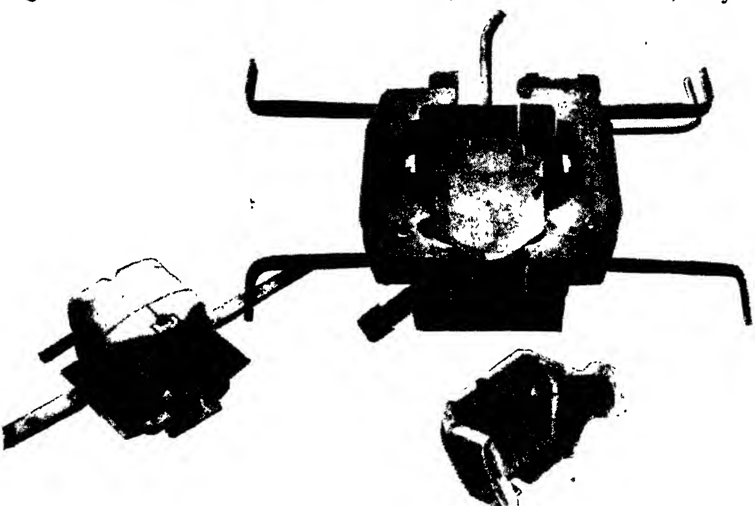


FIG. 52.

sufficient to enable up to fifty thousand castings to be produced, so that the cost of the dies per casting may be quite low. The labour cost per casting is also reduced to a small fraction of that for a sand-mould casting. Thus die-casting is essentially a process for large quantity production; the minimium quantity for which the cost per casting will come out less than for sand-mould castings depends on the cost of the dies and on the saving effected in the labour costs; it may be as low as five hundred but usually is a thousand or more. The dies fail eventually because their surfaces "craze," that is, they develop a network of fine cracks and ultimately break up. The life of the cores is generally much shorter than that of the dies themselves and the cores may have to be replaced several times during the life of the dies. A fairly complicated set of dies and cores is shown in Fig. 52. Occasionally sand cores are used in connection with gravity die-casting.

Pressure Die-Casting. This is very similar to the gravity process but the metal is forced into the dies under considerable pressure, ranging from 400 lb. per sq. in. up to 25,000 lb. per sq. in. The dies are frequently water cooled, partly to keep their temperature down and partly to equalise the temperature throughout them. The dies may be made of mild steel or a plain carbon steel, but alloy steels will give longer lives. Two steels that are commonly used have the compositions, carbon 0·45, manganese 0·75, chromium 0·85, and carbon 0·37, chromium 5·25, tungsten 4·5, and cobalt 0·5. The former is used chiefly for zinc base alloys, and for small quantity production. The latter stands up to the action of the aluminium base alloys and may have a life several times that of the former. The pressure process requires special machines and these are of two main types: (1) Machines in which the metal is forced into the dies by means of compressed air acting on the surface of the molten metal in a closed pot that is connected to the dies by a spout, as shown in Fig. 53; and (2) Machines in which a piston or plunger is used to force the metal into the dies, as shown in Figs. 54 and 55. One drawback of the first type is that the molten metal in contact with the compressed air absorbs gases which may subsequently cause porosity in the castings. In both types of machine the opening and closing of the dies is usually done by power, either hydraulic or compressed air or a combination of both, but cores and inserts have usually to be put in or "set" by hand, though automatic setting is sometimes arranged. The cycle of operations is sometimes automatic; thus the closing of the dies, the injection of the metal, the pause for solidification of the metal, and the opening of the dies and the ejection of the casting all follow in correct sequence every time the operating control is actuated. In all machines the ejection of the casting, if it does not leave the dies naturally, is done automatically, but the ejector arrangements are chiefly a matter of die design. With fully automatic machines a production of 1,000 "shots" per hour can be achieved on small, simple castings and on fairly complicated castings rates of 200 per hour are attainable. On the other hand, a fully automatic machine cannot usually be operated economically on batches of less than about 3,000.

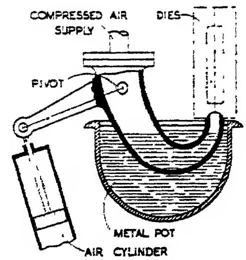


FIG. 53.

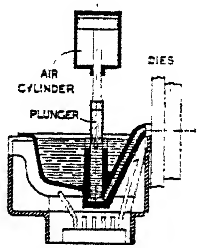


FIG. 54.

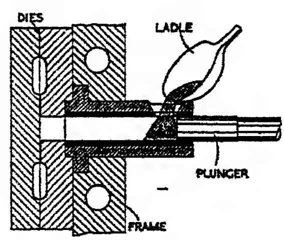
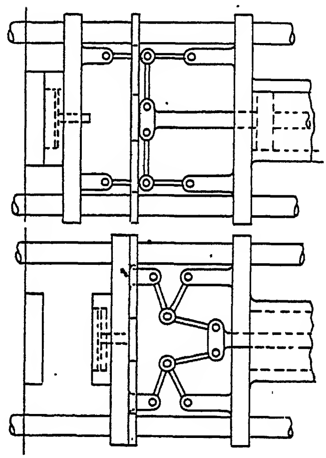


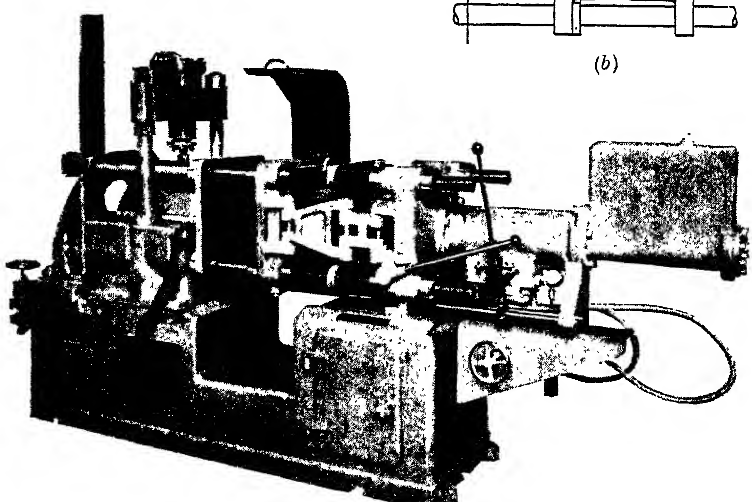
FIG. 55.

When zinc base alloys are being cast the injecting cylinder and plunger may be submerged in the molten metal as in Fig. 54, which will run into the cylinder through suitable ports by gravity alone and then be forced into the dies by the stroke of the plunger. With aluminium base alloys and with higher melting-point copper alloys it is not practicable to have the injector cylinder submerged in the molten metal and so the metal is poured from a ladle, through a port, into the cylinder just before the moment of injection as in Fig. 55 ; alternatively, compressed air injection is used.

The E.M.B. Pressure Die-Casting Machine. As an example of a typical pressure die-casting machine one of the range manufactured by the E.M.B. Co., Ltd., of West Bromwich, will be described. The author is indebted to the manufacturers for the supply of photographs and information. The machine, which is shown in Fig. 56 *a*, is intended for zinc base alloys and the injection cylinder is submerged in the molten alloy in the melting pot. The latter is carried in a housing which is supported on the main frame in such a manner as to insulate it thermally from the rest of the machine and to allow for any distortion that may occur through prolonged heating. Heating is normally



(*b*)



(*a*)

FIG. 56.

by gas burners but oil heating can be provided if required. The dies are carried on platens which are free to slide along four guide bars. The left-hand platen, adjacent to the melting pot, carries the sprue half of the die and its motion is restricted by collars on the guide bars to about half an inch. The right-hand platen is moved to and fro by a piston which operates through a double toggle linkage as indicated at *b*. The piston is actuated by compressed air and the air pressure is adjustable. The speed of actuation is regulated by an oil dash-pot (seen on the extreme right) which is fitted with valves controlled by the vertical operating lever seen near the right-hand end of the machine. This platen movement can be halted at any moment, during either opening or closing, by means of adjustable stops, for the purpose of setting or withdrawing cores or placing inserts. After such a halt the motion can be restarted by pulling the control lever forwards and moving it to left or right. The last part of the platen movement is used to operate the ejector pins of the die as may be seen from Fig. 56 *b*. Adjustment for different thicknesses of dies is obtained by nuts which regulate the position of the operating cylinder unit (which is carried on machined ways on the bed) along the guide bars. The injection plunger is operated by compressed air acting in the vertical cylinder seen above the melting pot and this air pressure is independently adjustable. The injection is controlled by the horizontal lever, which is mechanically interlocked with the vertical lever controlling the platen movement, so that injection cannot occur until the dies are properly closed. During the first ½ in. of the opening movement of the dies the left-hand platen is dragged along by the right-hand one and this breaks the sprue. The motion of the left-hand platen is then checked and the dies open.

Advantages of Pressure Die-Castings. Pressure castings can be made to closer dimensional tolerances than are feasible with gravity casting, the minimum tolerances varying from 0·001 in. on small zinc base alloy castings up to four or five times that amount in copper-base alloys. Aluminium base alloys require roughly twice the tolerances practicable with zinc base alloys. The surface finish of pressure castings is better than that of gravity castings and pressure cast metal has usually better mechanical properties than gravity cast metal. The actual time taken per casting is also generally much less than with the gravity process. Thus frequently a pressure die-casting will prove the cheapest method of production even though sometimes the cost of the castings, as they come from the dies, may be higher than the cost of other types of casting, because of the reduction in machining and finishing costs. Generally speaking the thinner the section of a pressure die casting (provided that complete filling of the cavity is assured) the sounder the metal will be, because of the more rapid cooling. It is better to use thin walls with stiffening ribs than to use thicker walls without ribs ; the rib spaces also

7

assist the flow of the metal. Sections as thin as $\frac{1}{32}$ in. can be cast with zinc base alloys.

External screw threads can be cast in the zinc and aluminium base alloys provided they are of a form, such as the Whitworth Vee, which will permit the auxiliary dies used to produce them to be withdrawn readily and provided the pitch is not less than about $\frac{1}{32}$ in. The use of auxiliary dies results in parting lines down each side of the screw and the slight fins produced may have to be machined away. This can be avoided by using a solid die which is inserted into the main die and which is removed with the casting when the dies are opened ; the die then has to be screwed off the casting. This method, however, slows up the production and machining the thread from the solid might be preferable.

Internal threads can be cast quite satisfactorily provided the hole is not smaller than about $\frac{1}{8}$ in. in diameter ; threaded cores are necessary and these must be screwed out of the casting before the latter is removed from the dies ; the unscrewing is frequently done by means of a lever, rack, and pinions. Small holes can, however, almost always be formed more cheaply by machining them from the solid and frequently it will prove cheaper to machine the threads of large holes rather than to cast them.

Pressure Casting Dies. The design of these is more difficult than that of gravity dies and it is best left to designers possessing the necessary experience. The remarks that follow are intended to do no more than introduce the reader to the elements of the subject. Dies may be divided into three classes: (1) Single ; (2) Multiple ; and (3) Combination. Single dies carry only one impression and produce only one casting per machine cycle or " shot." Multiple dies have several impressions of the same article formed in them and combination dies have several impressions but not all of the same article. Multiple and combination dies obviously cost more than single dies, but when large quantities are required will give a lower cost per article. Dies are also classified according to the position of the sprue through which the metal is injected. If the sprue is cut partly in one die and partly in the other the dies are called " split-sprue " dies. If the sprue passes through one of the die blocks (invariably it would be the fixed one) from the back into the impression the die is called a " solid-sprue " die. The determination of the position of the parting surface of the dies in relation to the casting is a matter of importance. The concentricity or relative position of a boss and a flange can be guaranteed to very small limits if both are formed in the same die block, but if the boss is formed in the fixed die and the flange in the moving die mis-alignment may occur. The positioning of the ejector pins by means of which the casting is ejected from the die calls for experience and judgment. Badly placed pins may

give faulty ejection and hold up production or may result in distortion of the casting and damage to its surface. The provision of adequate fillets in the corners of both castings and dies is important. The manufacture of pressure die castings is much more in the hands of specialists than is the case with gravity castings.

Die-Casting Properties of Alloys. The table below shows the characteristics of some of the common alloys in relation to die casting.

Alloy	*Characteristics*
Gunmetal	Difficult to pressure cast.
10 per cent aluminium bronze	Difficult to pressure cast but excellent for gravity process.
70/30 brass	Cannot be die cast.
60/40 brass	Good for pressure casting.
L.5	Unsuitable for pressure casting.
L.8 and L.11	Poor for pressure but good for gravity casting.
L.33	Excellent for pressure casting.

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Chapter 5

FORGING PROCESSES. DROP FORGING. MACHINE FORGING

Forging may be described, briefly, as the art of manipulating metals that have been heated until they are more or less plastic, by means of hammering, squeezing, and bending. Most forgings are made in steel, but other metals can be forged; for example, some of the brasses and many of the aluminium alloys. A forged material nearly always has better mechanical properties than a cast one, the difference being usually marked as regards toughness and impact strength. Also since most metals exhibit a "grain flow" or "fibre" after undergoing a rolling or forging operation, and then show a greater strength when tested "along the fibre" than when tested "across the fibre," the forging process provides a means of arranging the fibre so that the greatest strength is developed in the desired directions. As an example of this consider the gear wheel shown in Fig. 57 *a*, *b*, and *c*. In *a* the wheel has been turned out of a rolled bar and the grain flow is everywhere parallel to the axis, hence the teeth are being loaded across the fibre and will not be as strong as they are in example *c*. In the latter the wheel has been made by enlarging a rolled bar by means of a forging operation known as *upsetting*, the result of which is to produce a fibre as shown and the important stresses in the teeth now act along the fibre. In *b* the wheel has been turned out of a piece of rolled plate with the result that some of the fibres are in desirable directions but others are not. As another

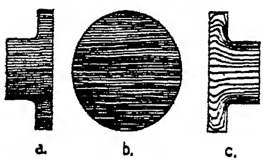


FIG. 57.

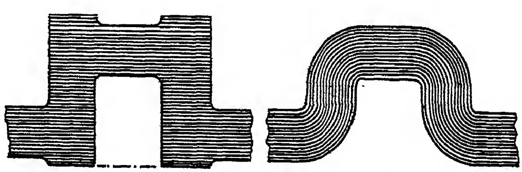


FIG. 58.

example consider a simple crankshaft. If this is made by forging a block down to form the shaft portions and then cutting out the metal between the webs, as indicated in Fig. 58 *a*, then the grain flow will be poor. If, however, the shaft is made by bending a shaft to the cranked shape desired then the grain flow will be as good as it can be. The grain flow

of a forging can be examined by taking contact prints (on a special paper) of its surface, after rough polishing and the application of a suitable reagent. These prints, when examined under low magnification (up to 10), will show the grain flow; this structural formation of the metal is referred to as the *macrostructure* to distinguish it from the crystal structure seen under higher magnifications, i.e. the microstructure.

Since all forging operations start with the heating of the metal to the forging temperature this operation will be considered first. Most forgings are made from *billets* or from pieces of bar material cut off by sawing or shearing. Billets are blocks of steel or other metal, usually rectangular or circular in cross-section, that have been made from cast ingots or parts of ingots, by hammering under steam hammers or squeezing under hydraulic forging presses. These forging operations on billets are usually done by the manufacturer of the steel.

The heating of billets requires careful control; if the heating is too rapid in the early stages there will be a danger of some steels cracking, and so large billets may have to be heated up with the furnace or to be put first into a furnace at a low temperature and later be transferred to another one at a higher temperature. If steel is heated to too high a temperature it will be "burnt"; its mechanical properties will be greatly impaired and cannot be restored except by remelting the metal. If steel is kept at the forging temperature for an excessive time grain growth will generally occur and again the properties of the steel will deteriorate; they can, however, be restored by suitable heat treatment (normalising). Unless the atmosphere inside the furnace is carefully controlled the surface of the billet may be unduly oxidised or it may, if it is a carbon steel, be robbed of some of its carbon, or be *decarburised* in the surface layers. Oxidising and decarburising can occur simultaneously and, sometimes, instead of losing carbon, the steel may pick it up. Large billets are difficult to heat to a uniform temperature and unequal heating may mean that parts of the billet are overheated, which is most undesirable, and that other parts are insufficiently heated, which may make forging difficult and lead to the formation of cracks.

In *smithying work* (the phrase covering relatively small jobs made by hand hammers or small power hammers) the work is frequently heated in a fire built up on a hearth, and is directly in contact with the fuel, which is generally coal or a mixture of coal and coke. Combustion is maintained by a supply of air under pressure to a tuyere at the back of the hearth. The products of combustion are carried off, by natural draught, through a hood that covers the hearth and which is connected with the chimney flue; alternatively a fan may draw the products down through the fire into underground flues. The determination of the temperature to which an object is heated in the smith's fire is a very difficult matter and considerable experience and skill are required to avoid overheating of the work.

Large billets, and work produced on a quantity basis using drop hammers and forging machines, are heated in specially constructed furnaces. These are of two main kinds: (*a*) *Intermittent*, *batch*, or "*in and out*" furnaces; and (*b*) *Continuous* furnaces. The first kind is essentially a rectangular box lined with refractory material and having a door or aperture at one end and gas or oil burners at the sides. In this type of furnace the work is put in, often by means of elaborate mechanical handling devices, and is left until it has reached the proper temperature, when it is removed. The continuous type of furnace is made in several forms, but in all of them the work is put into the furnace at one point and travels automatically through the furnace until it reaches the exit point, the speed of travel being adjusted so that the temperature is then at the required value. The fuels used are again gas, oil, and pulverised coal. One common form of continuous furnace is that in which the work enters at one end, travels in a straight line through the furnace, and leaves at the opposite end. In this type the work may be moved along by gravity, the hearth being inclined, be pushed through by a pusher mechanism at the entering end, or be carried through on a conveyor. The choice of method is not unimportant and many factors have to be taken into account, thus the tendency of billets to stick together when forced into contact at high temperatures may make the use of a pusher-type furnace impossible, and whereas this type might possibly be satisfactory with cylindrical billets it might be unsuitable for square section ones. For a full consideration of the problems involved the reader is referred to books dealing with furnace construction and operation. A second common type of continuous furnace employs a rotary hearth.

In modern installations furnace temperatures are measured by means of thermo-couples placed at various points throughout the furnace, and the indicating instruments for a group of furnaces are commonly grouped together in an instrument room. Temperatures are also measured by means of optical pyrometers. The principles underlying the action of thermo-couples and optical pyrometers are outside the scope of this book and the reader is referred to books on physics and on such instruments. Furnaces can be, and sometimes are, automatically controlled so that the temperature is maintained at the desired value; this, however, by itself does not ensure the work being heated to the correct temperature. This is because the furnace must be maintained at a higher temperature than is required in the work in order to keep the time of heating reasonably short, and so if the work is left in too long it will be overheated; also, of course, if it is removed too soon it will be underheated. The pusher and conveyor types of continuous furnace are better in this respect since the time the work is in the furnace is determined by the speed of operation of the pusher or conveyor. In the gravity type the work must be removed at the exit end and fed in at the other end regularly, or the temperature of the work will vary despite the constancy of the furnace temperature.

Heating furnaces are sometimes provided with "artificial atmospheres" in order to prevent undue oxidation, carburisation, or decarburisation of the contents. Among the gases used for this purpose are "charcoal gas" (a mixture of carbon monoxide and dioxide), cracked ammonia gas (a mixture of nitrogen and hydrogen), and gases generated from cast iron swarf, old carburising material, etc. The furnace atmosphere can also be controlled by varying the proportions of fuel and air admitted to the burners; if the air is restricted then generally a reducing but decarburising atmosphere will be obtained, whereas excess air will give an oxidising atmosphere.

The refractory linings of furnaces have to be patched up at intervals and some furnaces are specially designed so that these operations can be carried out expeditiously, even, in some cases, while the furnace is in operation.

Common Forging Operations. The principal operations by means of which the smith transforms the billet into a forging are *upsetting*, *drawing-down*, *bending*, *punching*, *cutting-out*, and *welding*, and these will now be briefly described.

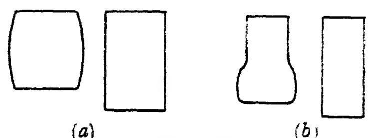


FIG. 59.

Upsetting is a process whereby the cross-sectional area of a billet is increased, the length being correspondingly reduced. If a cylindrical billet is heated uniformly to forging temperature and is then placed on end on an anvil under a hammer and is struck, it will be deformed as shown in Fig. 59 *a*. If only one end of the billet were heated then the deformation would be as shown at *b*, and by heating in the middle only or, which comes to the same thing, by quenching the ends, an upset may be obtained at any point in a bar. The amount of upset that can be obtained is limited only by the tendency of the bar or billet to buckle sideways rather than to set symmetrically. Upsetting is almost always one of the first operations performed in machine forging and is considered in greater detail in a subsequent section (see p. 116).

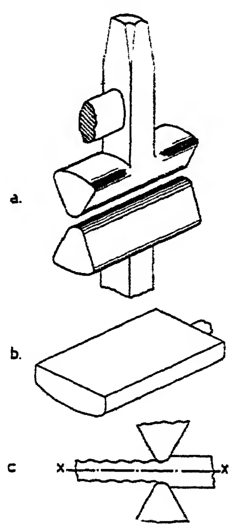
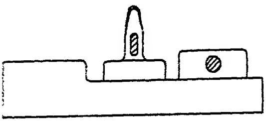


FIG. 60.

Drawing down is roughly the opposite of upsetting, being a reduction of the cross-sectional area of a piece with a corresponding increase in length. But whereas there is a fairly definite limit to the increase in cross-sectional area than can be produced by upsetting there is almost no limit to the reduction that can be produced by

drawing down. The operation is done most effectively by means of *fullers* or *fullering tools*, examples of which are shown in Fig. 60. The type shown at *a* is used for hand work, usually in pairs as indicated; the type shown at *b* is used for power hammer forging, the work resting on the anvil. The fullering tool localises the effect of the hammer blow and enables the deformation in the direction *xx* (Fig. 60) to be made greater than that perpendicular to *xx*. When the reduction of cross-section is large the operation may sometimes be done most economically between rotating rolls. *Setting down* is an operation similar to drawing down, but usually the thickness only is reduced. It can be done entirely with a fuller, except for the final finishing operation which is done by a *flatter* as indicated in Fig. 61, *a* showing a hand tool and *b* a power-hammer tool. Setting down is, however, often started by gashing the billet with a chisel as shown in Fig. 62. In drawing down bars of circular cross-section no attempt should be made to keep the section circular as this leads to cracks or splits being formed at the centre of the bar; the correct method is to work the bar into a hexagonal or octagonal shape until the cross-section has been sufficiently reduced and finally to restore the circular cross-section by means of *swages*, a pair of which is shown in Fig. 63. It will be noticed that the corners of the semicircular recesses are rounded off; this is important because otherwise there is a liability for fins to be formed as shown in Fig. 64, and as the work is turned round during the swaging these fins may get folded over as shown at *b*, thus producing *laps* which may result in the work being scrapped. Swages are made to produce other shapes than cylindrical and are commonly provided with a spring handle as indicated in Fig. 65.


(a) (b)
FIG. 61.

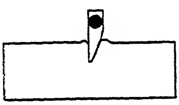


FIG. 62.

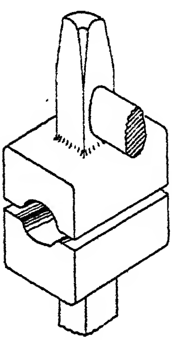
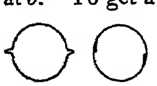


FIG. 63.

Little need be said about *bending* except to point out that a right-angle bend as shown in Fig. 66*a* cannot be obtained simply by hammering a piece of bar round the corner of an anvil; the result of that operation would be as shown at *b*. To get a bend as at *a* a bar must first be swaged down or upset to the shape shown at *c*; this type of bend should therefore be avoided if possible. Pipe bending is an important part of the work of some forges and is often done in a separate section. The chief difficulties in pipe bending are: (1) Flattening of the bends; (2) Keeping the straight portions in their proper planes. The first difficulty can


(a) (b)
FIG. 64.

largely be obviated by filling the pipe with some soft material, such as sand, lead, etc., before bending; the second difficulty can be reduced in magnitude by the provision of suitable jigs on which the pipes can be bent, but great skill is required nevertheless. *Punching* is used as a means of forming holes in forgings and consists simply in driving a punch of the proper shape into the heated work while the latter is supported on a block that has in it a hole slightly larger than that being punched. The punch is tapered and is not driven through entirely from one side since this would produce a tapered hole and a distorted plate as shown at *a*, Fig. 67; instead the punch is driven about two-thirds through and the work is then turned over and the punch driven through from the other side, thus producing a fairly parallel hole and avoiding distortion of the plate as shown at *b*. *Cutting out* is the process of removing pieces of metal from a billet by means of a chisel so as to shape it as required. Chisels for hand use are commonly made with a bevelled edge as shown at *a*, Fig. 68, but for power hammer work they usually

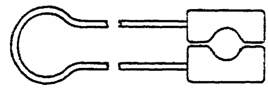


FIG. 65.

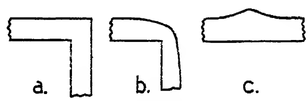


FIG. 66.

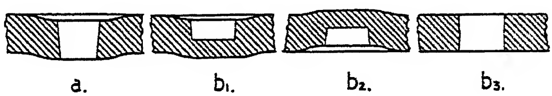


FIG. 67.

are shaped as shown at *b*. For cutting out the corners of recesses chisels are often made L-shaped. Cutting out, like punching, is usually started from one side of the work and finished from the other side. *Welding*, when done in the forge, consists in heating the parts to be welded up to the welding temperature, which is a good deal higher than ordinary forging temperatures, and then hammering them together so that the crystal grains of the one are united to those of the other. To get a good weld the surfaces of the joint must be clean and free from scale, and to ensure this a flux is generally used; its function is to lower the melting point of the scale so that the latter may be squeezed out of the joint when the parts are hammered together. Common sand, borax, and a mixture of borax and sal-ammoniac in the proportion of 4 to 1, are the most common fluxes and these are sprinkled on the faces to be joined just before the parts are hammered. The flux is fused by the heat of the metal and forms a liquid covering for the faces being joined; as the parts are hammered together this covering, together with any dirt or

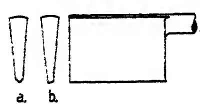


FIG. 68.

scale that may have been present, is exuded from between the faces. It is important, therefore, that those faces should be shaped so as to facilitate this exudation; they are consequently generally rounded, as shown in Fig. 69, and the hammering is started at the middle of the joint and is worked out to the ends. The type of weld shown in Fig. 69 is the commonest and most satisfactory type; it is called a *scarf weld*. Other types are the *butt weld* and the *tee weld*; these are shown in Fig. 70 but are not very satisfactory types owing to the difficulty in getting scale and dirt out of the joint and in hammering the joint properly. The strength of a forge weld is rarely equal to that of an unwelded bar of the same cross-section.

Fig. 69.

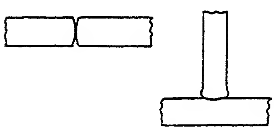


Fig. 70.

Forging Presses. The hydraulic forging press consists essentially of a ram guided in the frame of the press and carrying the moveable upper anvil beneath which, on foundations, is the fixed lower anvil. Hydraulic pressure applied to the ram enables a slow "squeeze" to be given to an ingot or forging placed between the anvils. Low-pressure water is generally used for the idle motions of the ram and high-pressure water, supplied by a steam intensifier, for the actual working motion. Steam cylinders are often used for lifting the ram and anvil upwards. The hydraulic forging press is particularly suited for handling very large forgings such as gun tubes, ships' mainshafts, alternator rotor shafts, etc., because the effect of a hammer blow on a large mass of metal is felt chiefly at the surface and very little at the inside of the mass, whereas the squeeze of the hydraulic press produces a flow that is fairly uniformly distributed throughout the cross-section of the metal. With simple forgings of the type mentioned a greater dimensional accuracy can be obtained with the hydraulic press than with the steam hammer.

Drop Forging. When a number of forgings have to be made to the same design the time required per piece can be reduced by making up special tools, bending jigs, etc., but the saving of time that can be effected by these means is never very great and so for large quantities drop forgings or machine forgings, which can be produced much more cheaply than hand forgings, provided a sufficiently large quantity is required, are used. In the process of drop forging, or stamping, the finished shape of the forging is obtained by stamping a hot billet of metal between an upper and a lower block of metal or *die*, in each of which an impression has been formed, the combined impressions being equal in shape to the forging required. The lower die block is usually fixed and the upper one is lifted up and allowed to fall on to the metal which is placed on the

lower die. The operation is done in a machine called a *drop-stamp* or *drop-hammer*, of which there are three main types: (*a*) the *strap* or *belt hammer*; (*b*) the *board hammer*; and (*c*) the *piston* or *steam hammer*. An example of the first is shown in Fig. 71. The bottom die is secured to the anvil which is supported on extensive foundations; these are insulated from the ground, as far as possible, as regards vibration and shock, so as to reduce the vibration of adjacent machinery to a minimum. Carried on the anvil block are guide frames between which the "tup"

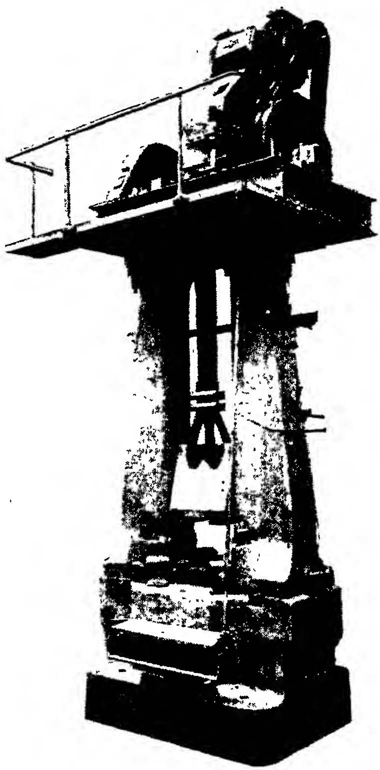


FIG. 71.

that carries the upper die block is free to slide. The guide frames serve to support the lifting gear seen at the top of the machine and which is controlled by a lever or cord conveniently placed for the operator. The lifting mechanism serves to lift the tup up to any position in the guides and to hold it there for short intervals; on releasing the control the tup falls by gravity. The energy of the blow given to the metal between the dies depends, of course, on the weight of the tup and the height to which it is lifted. Drop hammers are usually rated by the

weight of their tups; it may be mentioned that the anvil and foundation block usually weigh about twenty times as much as the tup. Drop hammers are made with tups ranging up to 10 tons. Various types of lifting mechanism are in use but a friction band-clutch arrangement

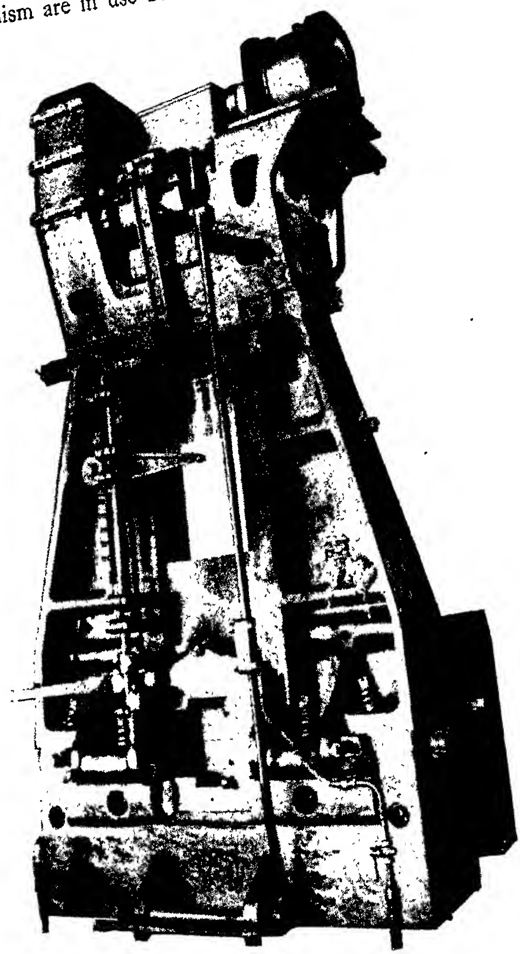


FIG. 72.

is, perhaps, the commonest. This type of hammer is often erected in "battery" form, the framework carrying the lifting gear and the drive to that gear being common to a number of hammers; modern tendency is towards self-contained hammers. The *board hammer*, an example of which is seen in Fig. 72, is similar to the strap hammer in general design,

the main difference being the lifting mechanism. This takes the form of a board (usually of hickory) that is fixed to the tup at the bottom and which lies between a pair of rotating rollers at the top of the machine. The rollers, being carried on eccentric bearings, can be made to grip the board and thus lift the tup. This type of hammer is widely used in America but is used only to a small extent in England. The third type of hammer is becoming popular both in England and in other countries and an example is shown in Fig. 73. It is built on the lines of an ordinary

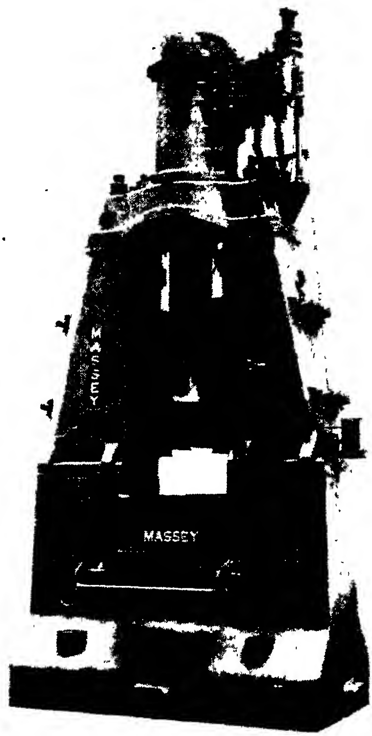


FIG. 73.

steam hammer and the tup is usually integral with the piston rod. The blow of the tup is augmented by steam pressure acting on top of the piston during the working stroke and thus, for a given weight of tup, a heavier blow can be given. This type of hammer also provides better alignment of the two dies than the other types and thus gives more accurate forgings. It should be noticed that aluminium alloys of the duralumin type offer about twice the resistance to deformation of ordinary steels and about one and a half times that of nickel-chrome steels, all the resistances being taken at the optimum forging temperature for the respective metal. Hence piston hammers are much used for aluminium alloy forging.

Methods of Drop Forging. Drop forging can be done in two ways, which may conveniently be treated separately. In the first method the dies have only one impression in them, as in Fig. 74, and the heated metal, having been placed between the dies, is finished to shape by two or three drops of the tup. With simple forgings the work can be completed from the billet in a single pair of dies, but for complicated shapes either the billet must be given some preliminary shaping under an ordinary hammer before it is finished in the drop hammer, or, alternatively, two or more pairs of dies must be used. In the second method of drop forging any preliminary work that may be necessary is done between the dies in the drop hammer and these are provided with several pairs of impressions to enable this to be done, as can be seen in Fig. 75. In this second method the stock used is generally bar stock and the

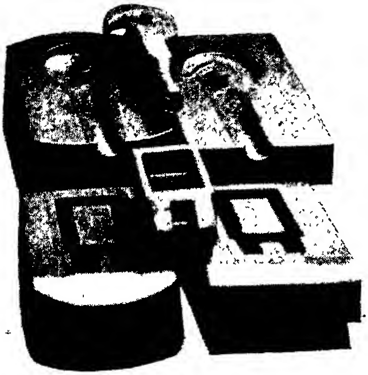


FIG. 74.

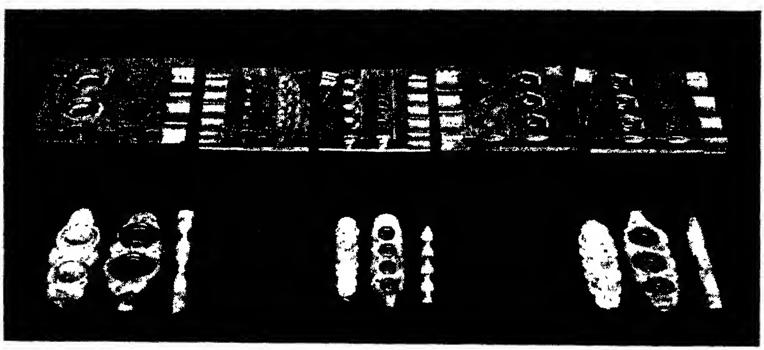


FIG. 75

forging is not severed from the bar until it has been finished by striking between the finishing impressions of the dies; the cutting off may be done under the drop hammer. To prevent the forging sticking to the dies, particularly in the bottom die, a little sawdust, coal dust, or oil is sometimes put on the dies just before the actual blow is delivered. With aluminium alloys copious supplies of oil are sometimes used.

Drop Forging Dies. It is probably obvious that the impressions in the dies must not be undercut at all or the forging cannot be removed

from the dies; this sometimes means that the parting surface between the dies must be a curved surface. Whenever possible plane parting surfaces are used and curved surfaces can sometimes be avoided by forging an article flat and then bending it in a subsequent operation. The die impressions must also be given adequate *draft*, that is, the surfaces that lie approximately vertical must be inclined to the vertical at a small angle, which ranges from as low as 3 degrees up to as much as 10 degrees for steel and 15 degrees for aluminium alloy forgings. A common draft angle is 7 degrees. Allowance must also be made for the contraction of the forging on cooling; this is commonly made $\frac{1}{8}$ in. per ft. for both steel and aluminium alloy forgings, the higher coefficient of expansion of the latter being offset by the lower finishing temperature. In order to ensure the complete filling of the die impressions the billet used is made somewhat heavier than the ultimate finished forging. The excess metal is squeezed out between the faces of the dies and forms a *fin* or *flash* all round the forging at the parting line. This flash is removed

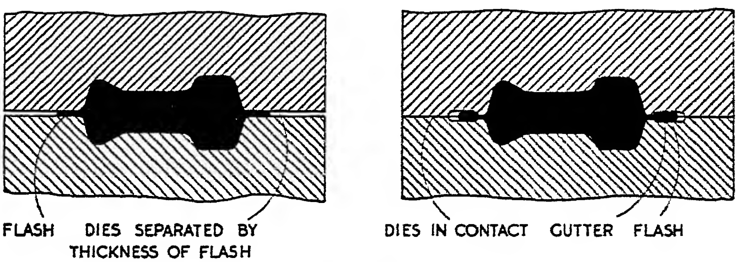


Fig. 76.

in a subsequent operation but it is necessary to allow for a definite thickness of flash when the depths to which the die impressions are to be sunk are being settled. Because the flash cools down much more rapidly than the body of the forging a large proportion of the energy of the last blow of the tup may be absorbed in the flash and it may be difficult to get forgings consistently to size. This may be obviated by sinking the die impressions full depth and providing a gutter for the flash as shown in Fig. 76. Hammering is then continued until the dies are heard to " rap," that is, until the die faces come into contact; this enables greater consistency to be obtained in the thickness of the forging. The centre of the impression should be at the centre of the face of the die block in order to keep the thrusts fairly central, and to eliminate tilting and consequent guide wear as much as possible the edges of the impression should preferably not be less than 2 in. from the edges of the die block. Opinions differ as to whether a multiple impression die is better than separate roughing and finishing dies; the die sinking costs are rather higher for the multiple impression die but the cost of die steel is lower; the risk

of the multiple impression die being scrapped is rather higher but the production times are generally lower. English practice seems to favour the use of separate dies, while American practice favours the multiple impression die.

After leaving the drop hammer the job goes to a *trimming press* to have the flash removed; this is done by pushing the job through a die which has a hole in it whose shape is the outline of the job on the parting surface, by means of a punch carried in the moving head or ram of the press. The punch fits the hole in the die, leaving a small clearance all round and so when the job is pushed through the flash is sheared off. The bottom surface of the punch may be shaped to fit the top surface of the job. Trimming is commonly done immediately after stamping but sometimes the job is allowed to cool first; this reduces the risk of the job being distorted by the operation. Trimmer dies are given a clearance angle, as indicated in Fig. 77, which ranges from 18 degrees for thin dies up to about ½ in. in thickness, down to 6 degrees for dies 3 in. or more in thickness. By using a fine band saw it is possible to cut the punch out of the block of metal used for the die. Fig. 78 shows the various stages in the production of a duralumin connecting rod.

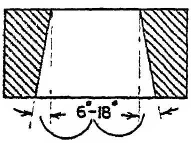


Fig. 77.

When a pair of dies is put into a drop hammer their alignment is generally checked by stamping a clay sample. The dies must be warmed

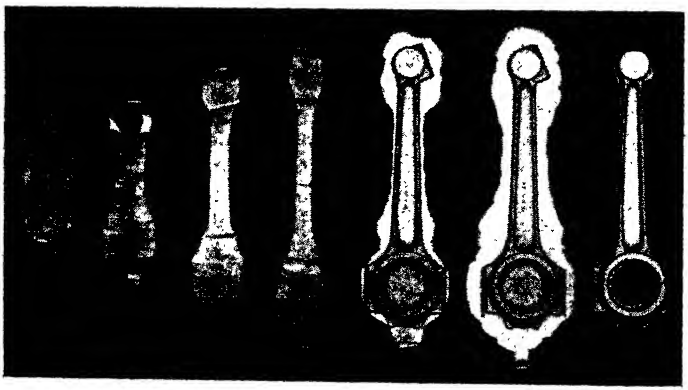


Fig. 78.

up before being used for stamping and this is done by putting a heated piece of metal between them. Pre-heating of the dies is particularly important with aluminium alloys, as these have rather a narrow range of temperature in which forging is possible. These alloys also do not flow nearly so readily as steels and the stresses set up in the dies are frequently greater than with steel, the die life being correspondingly lower. When

in use the temperature of the die faces will range from 150° to 250° C. in the heavy parts and up to 450° to 500° C. in thin parts and corners. The bottom die will generally run hotter than the top one because the hot forging lies on it during the idle time between the blows of the tup. Too little draft on the dies will cause the forging to stick in them and this will make them run hotter than normal and will result in more rapid wear. The life of a pair of dies is determined either by the occurrence of wear or " growth " so that the forgings become bigger than the prescribed limit, by the formation of " checks " or cracks at the corners of the impression, or, occasionally, by actual fracture of the die block. Dies have been found to give a longer life when used continuously than when used intermittently on small batches; for example, a continuous run gave a life of approximately 15,000 forgings whereas, when producing batches of 100 at a time, the life was only 2,000 forgings. The rate of production will also increase considerably after the dies are first put into operation and as the operator gets used to them.

In England the bottom die is usually secured to the anvil by four screws or " poppets " (these can be seen in Fig. 71) and so the bottom die can be aligned with the top one by adjusting the poppets. The top die is secured to the tup by having a dovetail formed on it, a corresponding dovetail being machined in the tup and a key being driven in to tighten up the connection. The bottom die is sometimes dovetailed and keyed to an adaptor which is held on to the anvil by the poppets. This eliminates most of the wear on the anvil that occurs when an adaptor is not used. In America both the dies are usually dovetailed and keyed. " Locked dies " are sometimes used, particularly in America, an example being shown in Fig. 79; the locking faces are usually circular in plan but can be rectangular if desired. Such dies help to prevent misalignment and consequent inaccuracy in the forgings. When the parting faces of the dies are non-planar locked dies are practically imperative.

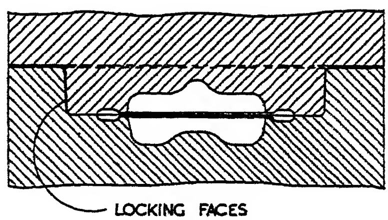


FIG. 79.

Materials for Dies. Drop forging dies are made either of a plain carbon steel, sometimes with a small percentage of vanadium in addition, or of a nickel-chrome-molybdenum steel. Four typical compositions are given below:

Carbon	*Manganese*	*Nickel*	*Chromium*	*Molybdenum*
0·5 –0·65	0·6–0·8	—	—	—
0·6 –0·75	0·2–0·4	—	—	—
*0·75–0·9	0·2–0·4	—	—	—
0·5 –0·7	0·5–0·9	1–2	0·5–1·0	0·15–0·35

* Plus 0·3 vanadium.

The British Standards Institute has formulated four standard compositions for die-block steels. These are given in British Standard Specification No. 224—1938. The manufacture and heat treatment of die blocks requires considerable experience for success to be attained and is largely done by the steel firms who make the steel, blocks being sometimes delivered to the drop stamping establishment in a fully heat-treated condition ready for the machining of the impressions. The process may therefore be considered to be outside the scope of this book, but in order that the reader may realise the complexity of it a brief description will be given. The extent of the reduction of the billet in forging the die block is important because, unless considerable work is put into the billet the resulting die block will be poor in quality; the cross-sectional area of the billet is therefore made about three times that of the required block. Die blocks should be thoroughly normalised before machining commences. After machining, the impressions are often checked by making lead casts of them and these casts are sometimes kept so as to enable the die wear to be checked. The die block is then heated up to the required temperature for hardening; this heating, and all the other heatings also, must be done very carefully, the temperature being raised very slowly during the initial stages; putting a cold die block into a hot furnace will ruin it. When thoroughly heated the block is removed from the furnace and is placed on a grid standing in water so that the base of the block is about half an inch below the water level. This hardens the back of the block sufficiently to prevent any spreading in use. The upper face of the block, which has or will have the impressions formed in it, is then sprayed with water until the block is black for about one-third of its depth; the block is then quenched in oil at 300° C. and is transferred to a furnace at the same temperature for tempering. Tempering is done so as to make the scleroscope hardness value for the impression face about 58 for shallow impressions of simple design down to about 45 for impressions 3 in. or more in depth or of intricate design.

Cost of Dies and Die Life. The first cost of a pair of dies may range from only a few pounds for very simple small dies, up to a hundred pounds or more for large complicated dies. The die life may range from only a thousand or so up to 25,000 or more. The cost of a drop forging depends on the first cost and life of the dies to a great extent, but if the effective life of the dies is not wholly utilised the cost will depend on the number produced. As an example of the effect of quantity on the cost per piece a small forging weighing about 3 lb. may be cited. When 10,000 pieces were required the estimated cost per piece was 1*s*. 6*d*.; reducing the quantity to 5,000, 1,000, and 300 respectively increased the cost by 2, 13, and 50 per cent.

Production Rates of Drop Hammers. These can be indicated only very approximately. Small forgings weighing only a few ounces

can be produced at rates up to 200 per hour, motor-car connecting rods at about 100 per hour, while a six-throw motor-car crankshaft has been produced at a rate of 30–40 per hour. Production rates depend on many factors, of which the most important are the heating arrangements, the actual lay-out of the plant and the handling facilities.

Machine Forgings. These are forgings that are made on a forging machine, an example of which, together with a pair of dies and a header, is shown in Fig. 80. The forging machine uses dies which are similar

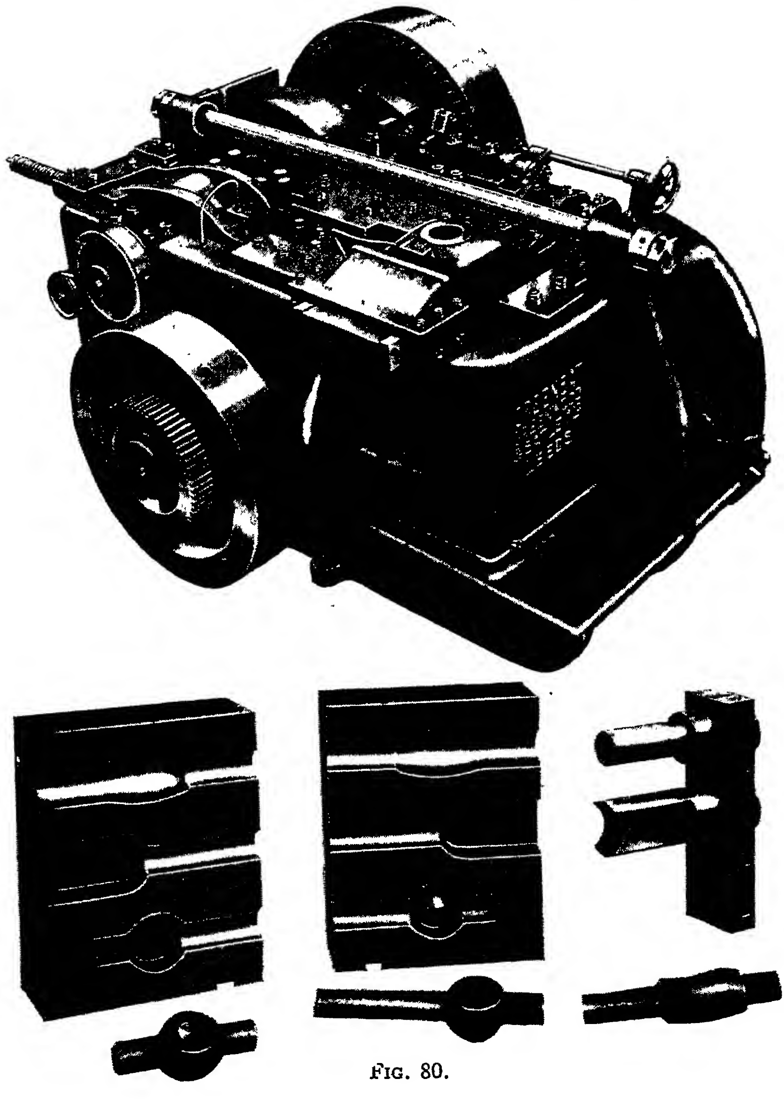


Fig. 80.

in many respects to those used in drop forging, but the majority of machine forgings have several operations performed on them by the forging machine and the dies have a corresponding number of impressions. One important difference between the drop hammer and the forging machine is that in the latter the movable die or dies are actuated mechanically by cranks and connecting rods and cams, the result being that the forming action is more of a squeezing action than it is in the drop hammer. The difference is thus somewhat like that between the steam hammer and the hydraulic forging press.

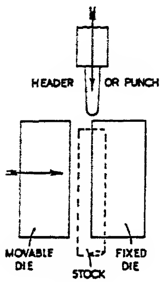


FIG. 81.

Most forging machines employ two principal movable members: a movable half-die and a " header " which carries a heading tool or piercing punch and which moves in a direction perpendicular to that of the half-die. The stock used is generally bar stock and it is put in from the end of the machine as indicated by the dotted lines in Fig. 81. One operation is very common in forging machines, namely, upsetting; this may be divided into (*a*) *unsupported*, and (*b*) *supported* upsetts. The former is indicated in Fig. 82; the stock is gripped by the side or gripping dies and the heading tool moves up and upsetts the bar. The distance *a*, the length of the bar that is unsupported, should not (according to most authorities) exceed $2\frac{1}{2}$–3 times the diameter of the bar. If this limit is exceeded the bar may buckle. In the supported upsett the sideways deflection of the bar during the upsett is limited because the deformation occurs inside a recess formed in either the dies or the header or both, as indicated in Fig. 83. In this type of upsett the diameter D of the upsett portion must not be greater than $1\frac{1}{2}d$, unless the unsupported length A is less than $3d$. Also the dimension *a* must be greater than A/2 or there will be a danger of the bar being mutilated as shown in Fig. 84. Tubes can be upsett equally well as bars, particularly when the inside diameter is unchanged, the outside diameter being increased, a punch being used inside the tube. The increased wall thickness should not exceed about $1\frac{1}{4}$ times the original wall thickness. Upsetts in the length of a bar can be made satisfactorily by using a sliding die as is indicated in Fig. 85, and two separate upsetts can also be produced simultaneously if required. The cutting off operation by which the finished forging is severed from the bar stock is generally done by a shearing blade carried by the movable die head and the final piercing

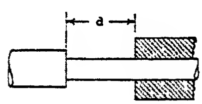


FIG. 82.

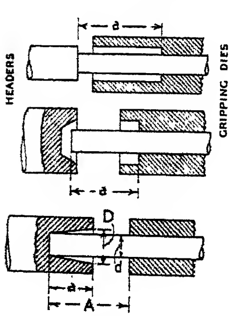


FIG. 83.

of a central hole in the forging may be done after the forging has been sheared off the bar, the shearing blade being used to support the work during the piercing operation. Alternatively the stock may be made smaller in diameter than the hole to be punched so that the punching operation also severs the job from the stock. The drawback to this method (which must be regarded as obsolescent) is that many more upsetting operations may be required to get the necessary increase of stock diameter before punching. The dies used in machine forging have to withstand different actions from those used in drop forging; the blow given is not so hard, but the hot metal is in contact with the dies for longer periods.

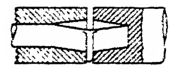


FIG. 84.

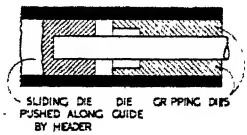


FIG. 85.

Shell Forging. Shells are commonly produced from billets sawn off circular bars in the smaller sizes, and from castings in the larger sizes, by means of a piercing operation followed by one or more drawing operations. The piercing operation is generally done in vertical hydraulic presses, but mechanical presses are occasionally used; the billet is put into a blind die (closed at the bottom) carried in a platen fixed to the frame of the press and the punch, which is carried by the ram of the press, descends and pierces the billet, the metal of which is "extruded" upwards between the die and punch. The forging then passes directly to the drawing press which is similar to the piercing press, except that the die is open at the bottom. The forging is pushed through the die by the punch, the walls being reduced in thickness and increased in length by the operation.

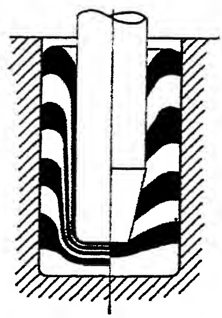


FIG. 86.

The shape of the end of the punch has a considerable influence on the way in which the material of the billet flows during the piercing operation, a flat-ended punch having less "piercing" action and producing a more extensive flow than a conical-ended punch, as is indicated in Fig. 86. Shells are also being forged by an operation which is partly a piercing and partly an extrusion one; the principle is indicated in Fig. 87. The punch A serves to form the base of the shell in the early stages but recedes

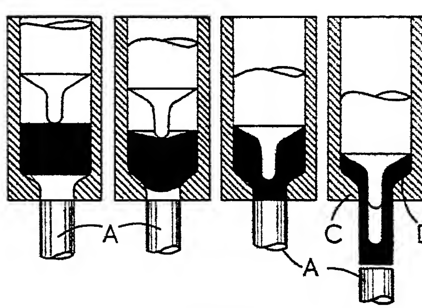


FIG. 87.

thereafter so that the base end is quite free during the last stages when the metal is being extruded through the space between the punch and the die C by the pressure exerted at the shoulder D. In America shells are commonly forged in forging machines by combined piercing and upsetting operations.

Electrically Heated Upsetting Machines. For simple upsetting operations, on comparatively small diameter stock, machines have been developed in which the stock is gripped in a pair of slidable jaws and is pressed comparatively lightly against a fixed head while a current of electricity is passed through the portion of the stock between the jaws and fixed head. That portion is consequently heated up, the temperature being highest at the fixed head and decreasing towards the jaws. When sufficient time has elapsed for the temperature to rise to forging temperature the pressure on the jaws is increased and those jaws move forward, thus upsetting the stock. This method of heating is extremely rapid and efficient. By using fixed gripping jaws which grip the stock only just firmly enough to give good electrical contact, and by applying a pressure at the free end of the stock so as gradually to force it through the jaws, the size of the upset can be made very much greater than by other methods. For example, a $\frac{7}{16}$ths dia. rod can be upset for a length of 6 inches.

The Accuracy of Forgings. Hand and hammer forgings cannot be held to close dimensional tolerances and these may range from as low as $\pm\frac{1}{8}$ in. in small forgings up to ± 2 in. in large ones. Drop forgings and machine forgings can be held to much closer tolerances, but it should be remembered that close tolerances mean increased cost because the dies will not have such long lives and the percentage of " wasters " will be greater. The Drop Forging Association of America has established a set of tolerances for drop forgings. For dimensions perpendicular to the parting surface the tolerances range from $\begin{smallmatrix}+0{\cdot}024\\-0{\cdot}008\end{smallmatrix}$ in. for forgings up to 0·2 lb. in weight, up to $\begin{smallmatrix}+0{\cdot}174\\-0{\cdot}058\end{smallmatrix}$ in. for forgings between 90 and 100 lb.; these are the " commercial " tolerances. A set of " close tolerances " of about one-half of the commercial values is also tabulated. For dimensions parallel to the parting surface, and to allow for shrinkage and wear, the tolerances range from $\pm 0{\cdot}032$ in. for forgings up to 1 lb. and $\pm 0{\cdot}003$ is allowed for each subsequent 2 lb.

Machining allowances have to be made on those parts of forgings that have to be machined to size. These allowances range from as little as $\frac{1}{32}$ in. in small drop forgings up to as much as 2 in. in large hammer forgings.

Defects in Forgings. The principal defects encountered in forgings may be summarised as follows: *Burnt metal, decarburised metal, seams,*

laps and *cracks*, "*corner ghosts*," *hair-lines and blowholes*, and *inclusions of dirt, slag, etc.* Burnt metal is generally indicated by the presence of a large number of small cracks on the surface of the forging and is a defect that cannot be remedied, so that the forging has to be scrapped. Decarburised metal is not a very common defect; it is shown up by the Brinell test, since it will lower the test figure considerably; it may not necessitate scrapping the forging. Seams and laps and cracks are due to incorrect forging practice and will usually cause the forging to be rejected. The fourth and fifth defects are ingot defects and must be blamed on the ingot maker. (Corner ghosts are fine cracks that are formed inside an ingot at the corners; they lie more or less radially and may persist through several forgings.) Hair cracks are very fine cracks, usually invisible to the naked eye, in the surface of large forgings; they may be due to incorrect heat treatment of the ingot during the cooling period; they may also be due to too rapid heating of billets.

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Chapter 6

PRESS-TOOL WORK AND SPINNING

Press-Tool Work. This phrase is used to describe a wide variety of processes by means of which articles are made from sheet material by cutting, bending, drawing, and stretching operations, all of which are performed cold. A certain amount of cold pressing and bending is done in forges but such work is not regarded as coming under the heading of press-tool work. The material operated on in press tools is usually fairly thin, seldom exceeding 10 S.W.G. in thickness, and the operations performed may be roughly classified as:

1. Piercing, blanking, and trimming;
2. Bending and forming;
3. Cupping and drawing;

but frequently all of these operations may be performed by a single stroke of the press used to produce an article.

Piercing, Blanking, and Trimming. These operations are essentially ones in which portions of a sheet of material are cut away so as to shape the sheet to the required form. In Fig. 88 is shown a simple piercing operation which is designed to cut a series of slots in a strip of material. The material or stock lies in a recess in the top of the die B which has formed in it a hole equal in shape and size to that required to be pierced. This die is mounted on the table or platen of a press and a punch C is mounted in the ram or movable head of the press. The punch is a free fit in the hole in the die and its corners are ground square so that on the descent of the ram a hole is pierced in the stock. The stock tends to cling to the punch and would be lifted up with it, away from the die, were it not for the *stripper* plate D which has a clearance hole for the punch to pass through and which is secured to the die. Some form of stop as indicated at E would also be provided so as to enable the pierced holes to be spaced at the proper distance apart. In an operation of this kind it may be the pierced strip that is required and the *slug*, or piece of material that is pushed through the die, that is the scrap, but more often it is the slug that is wanted and the pierced strip that is the scrap.

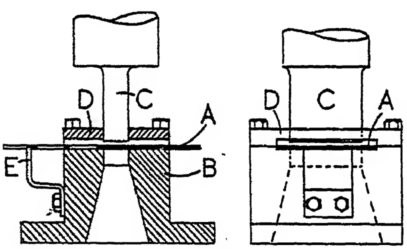


FIG. 88.

The action is essentially one of shearing the material and dies are made of hardened steel and are ground to sharp corners along the cutting edges. When these edges become slightly rounded the shearing action will no longer take place properly and the edges of the work will be ragged ; the punch must then be reground on its end so as to restore its cutting edges and the top surface of the die may also have to be re-ground. The presses in which these dies are used are considered in a later section.

The ram of the press is usually so adjusted that the punch enters the die for a short distance, but sometimes the end of the punch is brought just flush with the surface of the die. If the punch is adjusted so as to penetrate the material to a depth of not more than about two-thirds of the thickness of the material, and particularly if the edges of the punch are slightly rounded, the material will not be pierced but will have a recess formed on one side and a projection on the other side as indicated in Fig. 89. This kind of indentation operation is fairly common.

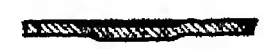


FIG. 89.

In Fig. 90 is shown a tool for producing circular blanks ; the blanking die A is held in the ram of the press and is formed with a recess slightly larger than the punch B which is fixed to the bolster plate of the press. A combined *pressure plate* and *stripper* C is used to grip the stock between itself and the bottom face of the die during the blanking operation and to strip the stock off the punch during the upward stroke of the ram and die. The blank, after being cut out, should remain on the top of the punch and is then removed when the material is slid along to the position for the next stroke. It may, however, tend to stick inside, and be carried up with the die, and to obviate this a spring-loaded stripper or ejector or, alternatively, a positively operated ***knock-out*** may have to be provided. An example of the latter is seen in Fig. 92.

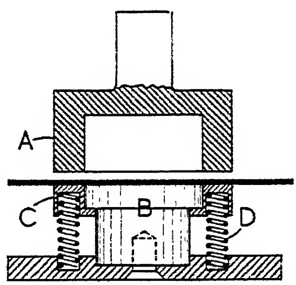


FIG. 90.

Trimming operations are essentially the same as piercing and blanking operations but are carried out on the edges of the stock or blank.

Compound Dies. These are dies in which blanking and piercing are carried out during the same stroke of the press. An example is shown in Fig. 91, where A is the blanking die, B the blanking punch, and C is the pressure-plate and stripper, the construction being essenti-

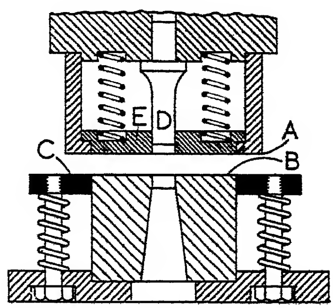


FIG. 91.

ally the same as in Fig. 90. The punch D pierces a hole in the blank and is arranged to act slightly after the blanking punch and die have cut the blank out. The plate E acts as a pressure-plate during the piercing operation and serves to prevent the pierced blank being carried up by the punch.

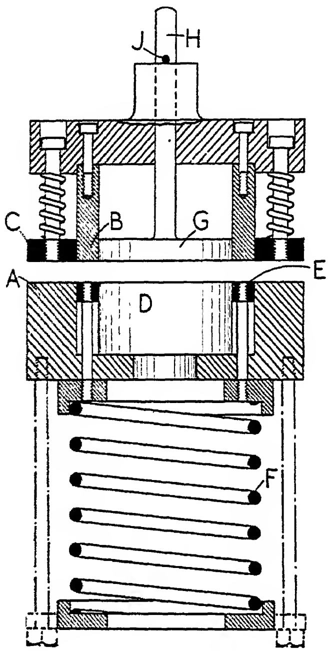


Fig. 92.

Another example is shown in Fig. 92 where the parts are, in comparison with Fig. 91, inverted. The blanking die A is now held on the bolster of the press and the blanking punch B in the ram. The pressure-plate C for the blanking operation is carried by the punch holder. The piercing punch is seen at D and the piercing die is formed by the recess in the punch B. The ring E acts as a stripper and ejector for the piercing operation, the pressure being supplied by a large coil spring F placed underneath the bottom die. The spring F and its abutment are frequently made part of the press and can be used with any die which may be put into the press; a rubber compression block may also be used instead of a coil spring. The pressure-plate C acts as a stripper for the stock and a knock-out pad G is provided to eject the scrap resulting from the piercing operation. As the ram of the press approaches its highest position the upper end H of the knock-out spindle strikes a fixed stop and the scrap is thus ejected from the inside of the punch B. The knockout pad is kept in place by the cotter pin J.

Progressive Dies. Two or more operations may also be performed at a single stroke of the press by mounting separate tools in series as is indicated for a simple blanking and piercing job in Fig. 93. The stock A is fed through the dies from right to left and is first pierced by the punch B and is subsequently blanked out by the punch C on the next stroke of the ram. Thus, although each piece requires two strokes to complete it, a piece is completed on every stroke of the ram. The stock must be positioned by suitable stops so that the pierced hole is centred properly relatively to the blanking punch C during the blanking operation.

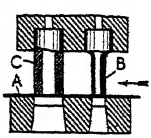
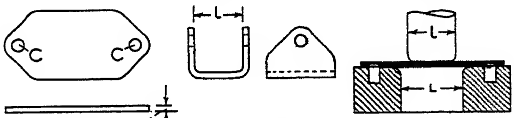


Fig. 93.

Dies of this kind are called progressive dies and are usually much cheaper to make than are compound dies, but the accuracy of the placing of the pierced hole relative to the outline of the blank is rarely as high as when the compound die is used and for this reason the latter is sometimes preferred.

Bending and Forming. A simple bending operation is shown in Fig. 94. At *a* is shown the initial shape of the work whose final shape is

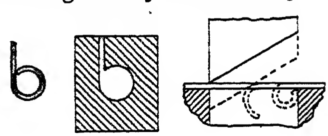


(*a*) (*b*) (*c*)

FIG. 94.

to be as shown by the views *b*; at *c* is indicated the method of bending. The blank is placed on top of the die and is positioned by shallow dowel pins which engage the holes C previously pierced in the blank. On the descent of the ram the punch bends the blank to the required shape. In this example the die can be made with a hole right through, but if the die is blind, i.e. closed at the bottom, or if the work has to be bent to some shape, such as a V, which precludes its being pushed through the die then some form of ejector may have to be provided. The width l of the punch must be less than the opening L of the die by an amount slightly greater than twice the thickness t of the blank. Commonly $L=2\frac{1}{4}t+l$.

If a piece has to be bent back on itself it will generally be necessary to use a more elaborate bending die with side sliding pieces which are moved inwards by ramps, carried by the punch, on the descent of the ram in order to complete the bending operation. Such dies are called *side-bending* or *side-closing* dies.



(*a*) (*b*) (*c*)

FIG. 95.

A rather specialised bending operation is one in which the edge of a strip or sheet is formed into a loop as shown in Fig. 95*a*; this operation is known as *curling* and can be done in a simple die such as is shown at *b*. Curling can be done at the same time as piercing by using a punch with an inclined face as shown at *c*. The curl can be made to encircle a wire so that the edge is stiffened and the operation is then known as *wiring*. Fig. 96 shows a die for wiring the edge of a cup-shaped member.

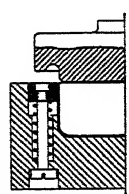


FIG. 96.

Cupping and Drawing. Cupping is the process of forming a flat disc or sheet, such as is shown at *a* in Fig. 97, into a cup as shown at *b*. Drawing is an operation that changes the cup shown at *b* into that

shown at c, the diameter being reduced and the depth increased. The cup need not be cylindrical but may be rectangular or, within limits, of any desired shape. A cupping operation differs essentially from a bending operation as will be appreciated when it is realised that the annular ring of material x, shown shaded in Fig. 97a, must be changed in form to the ring y, Fig. 97b, which is smaller in diameter than x; the material must thus be caused to flow considerably during a cupping operation. It is quite possible, and in fact is usual, for the thickness of the wall c of the cup to be considerably greater than the thickness t of the original blank. Hence it is usual for the punch used for a cupping operation to be made smaller than the die opening by an amount equal to about $2\frac{1}{2}$ times the thickness of the blank, t, so that an allowance equal to $\frac{1}{2}t$ is made for the thickening of the wall of the cup. The corners of the punch and die must be well rounded as shown in Fig. 98 and a lubricant such as tallow, lard oil, or soap suds is generally used. A cup whose depth is greater than about $1\frac{1}{2}$ times its diameter (or about half the blank diameter) cannot usually be made successfully in one operation.

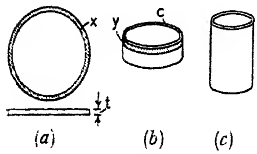


FIG. 97.

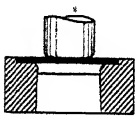


FIG. 98.

When soft ductile materials such as cartridge brass are being worked, cupping can be done with a simple punch and die as shown in Fig. 98 without any difficulty, but with harder and less ductile materials such as sheet steel, and with thin material there is always a liability of wrinkling occurring in the walls of the cup. This wrinkling can be largely, if not entirely, eliminated by using a *pressure-plate* or *blank-holder* during the operation. An example is shown at E in Fig. 99, which shows a combination die for performing blanking and cupping at a single stroke of the press. The punch A and die B first blank out the material and then the blank is drawn over the drawing punch C by the recess D in the blanking punch. During the drawing operation the edge of the blank is gripped between the pressure-plate E and the bottom face of the punch A, the degree of pressure being determined by the compression of the block of rubber F. This pressure has to be carefully regulated; if it is too low wrinkling may occur, while if it is too high the end of the cup may be torn away from the wall. When the holding pressure is supplied

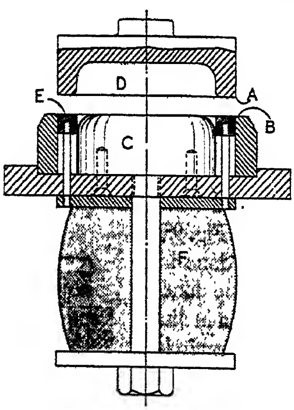


FIG. 99.

by a rubber block or a coil spring it must necessarily increase as the pressure-plate descends during the cupping operation ; this increase is not always desirable and it can be reduced to a very small amount by using an air cylinder, fitted with a piston, instead of a rubber block. The air cylinder is connected to a supply of compressed air and the holding pressure can easily be varied by varying the air pressure. In the die shown the pressure plate E also serves to eject the cup from the die.

The combination die enables the blank to be held during a drawing operation in a single-acting press which has only one moving part, namely, the ram or punch holder. For large drawing operations, however, a double-acting press is to be preferred.

Shape of Blank in Drawing Operations. For cylindrical cups the blank must obviously be circular but for a rectangular box the blank is made to the shape indicated in Fig. 100 and for other shapes of drawing the best shape for the blank must often be found by trial. If a rectangular blank were used to produce a rectangular box the corners of the latter would stand up above the level of the sides and the latter would be badly wrinkled.

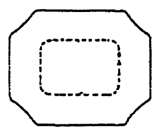


FIG. 100.

Multiple Drawing Operations. It has been mentioned that a cup whose depth is greater than about half its blank diameter cannot usually be successfully drawn in one operation. Deep cups must therefore be produced in several operations and an example is shown in Fig. 101. The

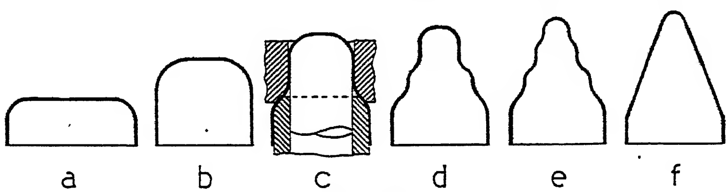


FIG. 101.

conical cap *f* is produced in seven operations, including the blanking operation which is not shown, and it will be noticed that not until the last operation is reached does the conical shape appear ; this is because provision has to be made in all the earlier operations for a pressure plate to grip the job, as indicated at *c*. This particular job is annealed twice during manufacture : after the second and fifth draws respectively. If an attempt is made to carry the drawing too far in one operation trouble will be experienced from cracking and tearing of the material.

Double Drawing Dies. Cups whose depths are about equal to their diameters can, however, be drawn in a single press cycle by using special dies which, in effect, enable two draws to be made successively for each stroke of the press. An example is shown in Fig. 102 which shows two

stages of the operation. A double-acting press is used and the blanking and holding punch A descends ahead of the hollow drawing punch B and blanks out the stock by entering the die C; the blank is then held

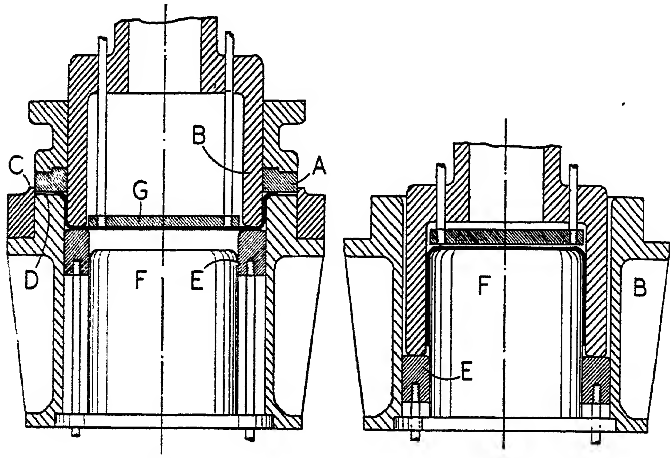


FIG. 102.

between the bottom of the punch A and the face of the bottom drawing die D. The punch B then descends and draws the blank into a comparatively shallow cup as shown at *a*. During this time the holder and ejector E, which is carried by the piston of a compressed air cylinder situated below the table of the press, also grips the blank lightly. Just before the drawing operation described is completed the flat portion of the blank comes into contact with the top of the second drawing punch F, and at this moment the pressure applied by the punch A is reduced and that applied by E is increased. The punch B then draws the blank over the punch F as shown at *b*, the original cup being turned inside out. The holder E serves to eject the finished cup if it tends to stick on the punch F, while the ejector G acts if the cup sticks inside the punch B. As an example of the size of cup that can be produced in this way it may be mentioned that a cup $6\frac{1}{4}$ in. diameter by $5\frac{1}{2}$ in. deep has been produced at the rate of 25 per minute from blanks 13·1 in. diameter by 0·024 in. thick.

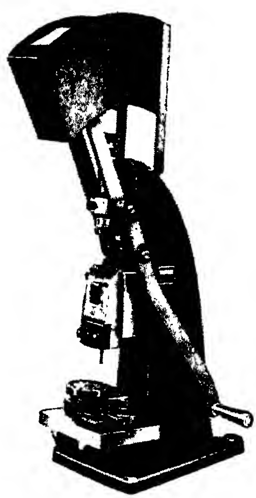


FIG. 103.

Types of Press. The presses in which press-tool work is done may be divided into (*a*) hand-operated presses, and (*b*) power-operated presses. Hand-operated presses are very simple in construction and are generally used only for small batches of simple work; an example is shown in Fig. 103.

Power presses may be subdivided into (1) Single-acting presses, (2) Double-acting presses, and (3) Triple-acting presses. Single-acting presses are essentially similar to the simple hand-operated press in that

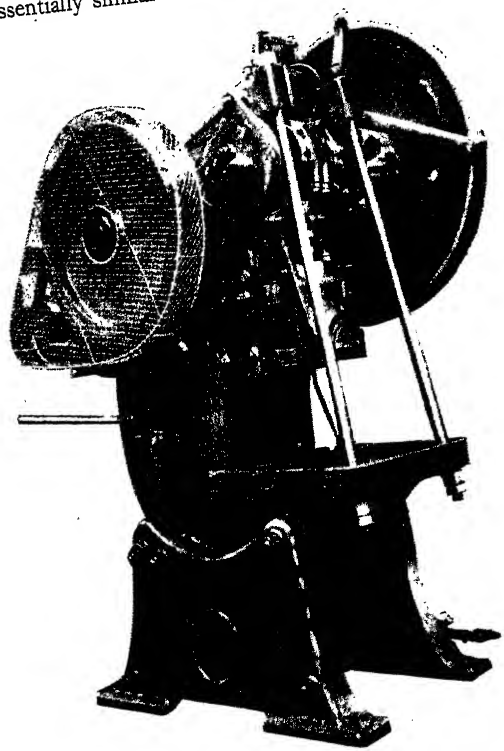


Fig. 104.

they have only one ram; the means of operating the ram are various. These means may be a crank, an eccentric or a toggle-lever mechanism. In Fig. 104 is shown a typical crank-operated single-acting press. The ram is guided in the frame and is actuated by a crankshaft through the medium of a connecting rod. The press is provided with a fly-wheel and may be driven either by a belt or by an electric motor. A clutch enables the flywheel to be coupled to the crankshaft when the press is required to work; this clutch may be arranged to disengage

automatically when the crankshaft has made one complete revolution and the ram has reached the top of its stroke, a brake being used to prevent over-running or, alternatively, the crankshaft may be allowed to keep on revolving as long as may be desired. In the latter case the feed to the stock must be automatic and the press must have additional mechanism to provide this automatic feed during the time that the ram and punch are clear of the work. Blanking, piercing, and trimming operations on strip material will generally be done with a continuously running press

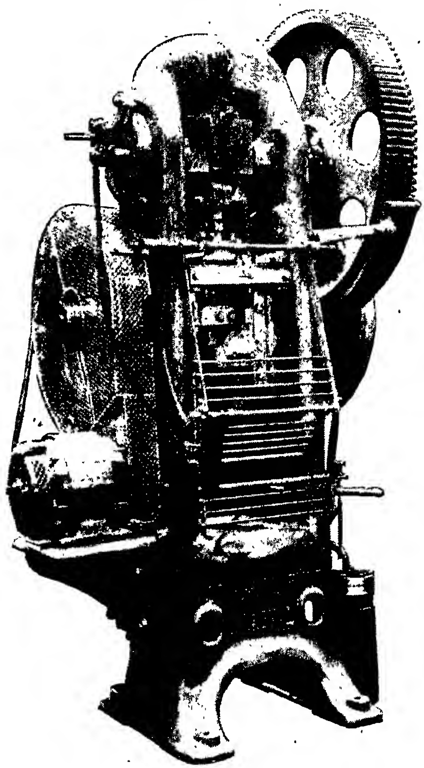


Fig. 105.

and automatic feed, but second operation work must generally be put into the die by hand and then the clutch must be operated every time the ram is required to make a stroke.

Because of the great danger to an operator's hands which arises from the starting of a press cycle before the operator's hands are clear of the dies all presses must, by law, be fitted with guards. These are arranged to push the operator's hands away (if they are not already clear) as the press ram begins to descend; the guard is clearly visible in Fig. 105. In addition some presses are arranged so that two levers have to be

moved simultaneously before the press will start and the levers are situated so that the operator must use both hands to move them. This, however, generally slows down production.

The use of an eccentric instead of a crank enables greater forces to be applied to the ram for a given diameter of shaft and is consequently found in presses for very heavy work. Very large presses, such as are used for the production of motor-car body panels sometimes have four eccentrics, one at each corner of the " ram," so as to ensure an even pressure and to eliminate tilting. When very heavy forces must be used as, for example, in coin embossing, toggle mechanism is sometimes used, but this form of operation generally necessitates a comparatively short working stroke.

Single-acting presses are made either *open fronted* as shown in Fig. 104, the frame being C-shaped, or *double sided* as in Fig. 105. They are often inclinable so that gravity may be used to discharge the job clear of the dies.

The double-acting press has two reciprocating parts, an inner member actuated usually by a crankshaft and connecting rod and an outer member actuated usually by cams carried by the crankshaft. Double-acting presses are used chiefly for drawing operations and the outer member is used to actuate the holder or pressure-plate, while the inner member carries the drawing punch. The use of cams makes it easy to arrange that the holder descends ahead of the punch so that the blank is gripped before the drawing starts and also to keep the holder at rest during the drawing. Double-acting presses do not usually run continuously.

A triple-acting press is similar to a double-acting press but has, in addition, a third reciprocating member carried in guides in the base of the machine so that a second punch can be made to draw the blank upwards into a suitably shaped recess formed in the top punch. They are used only for large work such as motor-car body panels.

Bulging Dies. A shape such as that shown in Fig. 106 cannot be produced by any ordinary punch and die and when such shapes are required they must be produced either by special bulging dies or by spinning. In the former process the dies are made in two or more parts, as indicated in the figure (in order that the finished job may be extracted), and the bulging is done by placing a block of soft rubber inside the blank, after it has been placed inside the dies and the latter have been clamped together. The punch on descending compresses the rubber and sets up the necessary radial pressure to stretch the metal until it fits the dies. The life of the rubber is commonly from 600 to 1,000 pieces. For details of other uses of rubber in press-tools the reader is referred to an article by F. L. Voyce in *Machinery*, September 11, 1941.

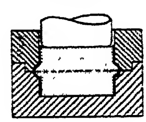


FIG. 106.

Sub-Presses. In an ordinary press-tool the upper member is carried by the ram of the press and the lower member is secured to the platen or table of the press; maintenance of the alignment of the two members depends, therefore, on the absence of any sideways or fore and aft movement of the ram relative to the platen, and as wear occurs in the ram guides misalignment and consequent damage to punches and dies may occur. This trouble is largely, if not quite entirely, eliminated by the use of *sub-press tools*. In these, an example of which is shown in Fig. 107, the bottom member is provided with two or sometimes three pillars that engage bushed holes in the upper member which is supported by springs. The alignment can be lost, therefore, only through the development of wear in the pins or bushes, and as a separate sub-press is used for each set of dies the wear is very small. The use of sub-presses makes the changing over from one job to another a much quicker operation and the idle time of the expensive press can thus be reduced. These sub-presses have, to some extent, been standardised and can be purchased " off the shelf " from the manufacturers.

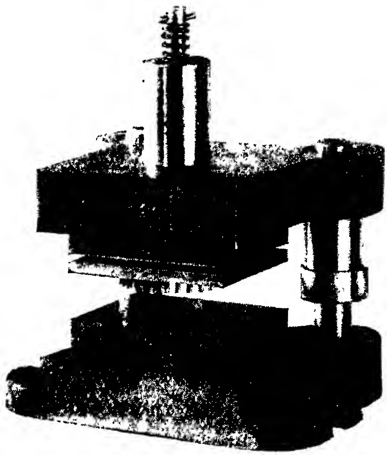


FIG. 107.

Production of Pressings in Drop Hammers. The development of all-metal aircraft has led to a great increase in the use of light alloy pressings and some of these are now being produced in special drop stamps using dies made of lead (containing 10 per cent of antimony) and of zinc. The zinc die is commonly made the bottom die and is cast from a wooden pattern; it is then used as the mould for the lead upper member, the contraction of the lead making the necessary allowance for the thickness of the sheet being drawn. The shaping of the sheet metal is done by a succession of light blows rather than by a few heavy ones and a lubricant is used to reduce the friction between the metal and dies. The life of the dies is low, being of the order of two to three hundred stampings, so that the process is essentially one for small quantity production. The drop hammers used are essentially the same as those used for drop forging but have larger, though lighter, anvils and more widely spaced tup guides so as to accommodate relatively large dies.

Metal Spinning. In this process articles are brought to their final shape by gradually deforming a disc or cup-shaped blank by pressing a

suitable tool against it while it is rotating in a special type of lathe. The shape of the article is settled by a former, made of wood or metal, on to which the metal is spun. The process is indicated in Fig. 108 in which A is the former, carried on the spindle of the lathe, and B is the blank, formed initially to the shape shown in the full line by a press-tool operation. The blank is held up against the end of the former by axial pressure applied through a ball-bearing "pallet" C which is carried in the tailstock of the lathe. When the blank is rotating at a suitable speed pressure is applied to it by a forming tool which may be hand guided or may be carried in a tool holder on the saddle of the lathe. The hand tools are made of metal and are provided with a wooden handle some 2½–3 ft. long. The end of this handle is placed under the armpit of the operator who then uses the tool as a lever, the fulcrum being provided by a pin D placed in a suitable hole in a T-shaped rest E fixed to the lathe bed. In this way the operator is able to exert localised pressure on the blank and thus to work it down until it fits snugly on the former, as indicated by the dotted lines. During the operation the fulcrum pin may have to be moved several times. In the early stages the blank is worked on to the nose of the former and assumes the shape shown inset in the figure. Lubrication of the contact between tool and work is usually necessary and is generally provided by rubbing lard oil, tallow, or some other lubricant on to the work by means of a piece of rag.

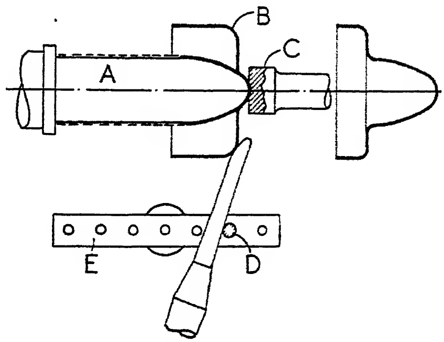


FIG. 108.

Clearly the shapes that can be produced by spinning are restricted to surfaces of revolution, that is, shapes whose sections by any plane perpendicular to the main axis of the article is a circle. Also, when a solid former is used, the diameter at the open end of the article must not be smaller than any diameter nearer the closed end or the article cannot be removed from the former. By using formers that are built up of several segments shapes such as shown in Fig. 109 can be spun. The use of built-up formers can sometimes be obviated by using a rotating "offset" former, an example of which is shown in Fig. 110. The blank is held up against the chuck A by end pressure applied by the member B which is free to rotate on the arm C carried by the spindle D which in turn is secured to the tailstock member E. A formed roller F is free to rotate on the outside of an eccentric bush that

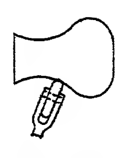


FIG. 109.

can be clamped in any position on the spindle D by means of clamp screws G. This enables the roller to be adjusted so as to bear against the inside of the blank, which starts with the shape shown in dotted lines. Another method of spinning such a shape is to start with a

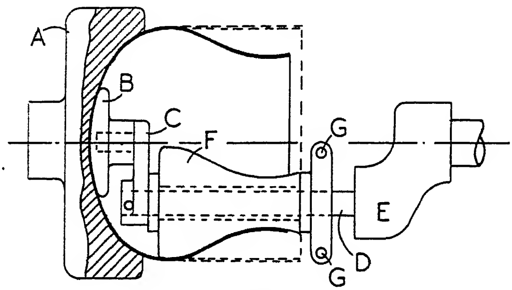


FIG. 110.

cylindrical blank whose diameter is equal to that of the opening of the finished shape and to enlarge it by applying a tool to the inside of it while a suitably shaped roller supports it outside. The process is then commonly referred to as a stretching process. It is indicated in Fig. 111 and is mostly used when the " bulge " in the article is comparatively small.

When a tool held in a holder in the saddle of the spinning lathe is used it generally takes the form of a roller that is free to rotate about its axis; such a tool is indicated in Fig. 109.

Any ductile metal can be spun, but brass, copper, aluminium, and mild

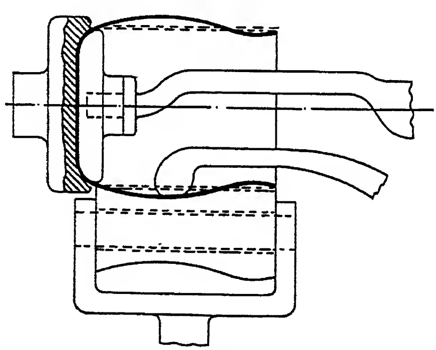


FIG. 111.

steel are the most usual materials. Tin-plate is also a commonly used material but requires special skill in order to avoid piercing the tin skin. As with a drawing operation in press-tool work, the material work-hardens during spinning and may have to be annealed several times

between the start and finish of the operation. Some materials also have to be warmed up by means of gas jets during the spinning in order to render them sufficiently ductile.

The formers and tools used in spinning are almost always quite cheap to make and so spinning is particularly suitable for the production of small quantities which could not economically be produced by press tools, and this is one of the principal fields for the application of the process.

The Dewey Process. This is similar in some respects to a spinning operation and enables a parallel tube to be formed, cold, to a tapered or sinuous shape and to have its wall thickness varied along its length as may be desired, within limits. This is done by pressing rollers against it as it rotates and by applying an axial push or pull according as to whether the metal has to be compressed and the diameter and wall thickness to be increased or vice versa. The process has only recently been developed and for a description of it the reader is referred to *Machinery*, June 12, 1941.

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Chapter 7

FABRICATION BY WELDING, BRAZING AND SOLDERING

The term " fabricated " is now used to denote articles that have been made from plates, angles, and other sections by welding, brazing, or riveting as opposed to manufacture by casting, forging, or press-tool processes. The essence of fabrication is the method used to join the pieces of which the article is built up, and as this is usually a welding process this chapter will be concerned chiefly with such processes.

Welding Processes. These may be divided into two main groups :

1. Pressure welds.
2. Fusion welds.

The characteristic of a pressure weld is that the metal being joined is never brought to a molten state ; it is heated up to a welding temperature and the actual union is then brought about by the application of pressure. In this group are forge welds such as have been described in Chap. 5 and *resistance electric welding.*

The characteristic of a fusion weld is that the metal being joined is actually melted and the union is produced on subsequent solidification. In this group are *gas welding* and *electric arc welding.*

Resistance Electric Welding. There are several resistance welding processes in use, the most important being *butt*, *spot*, *projection*, *seam*, and *flash* welding. In all of them the welding temperature is obtained by the heat generated by the passage of an electric current and the actual union is then brought about by pressure. In butt welding, which is used to join bars and plates together end to end, one bar is held in a fixed clamp in the butt-welding machine and the other bar in a movable clamp, the clamps being electrically insulated the one from the other and being connected to a source of electric current. The movable clamp with its bar is moved along so as to bring the ends of the bars into contact and the current is then switched on. Because of the higher electrical resistance at the contact between the bars the ends of the bars are heated up and quickly reach the welding temperature. During this stage the force pressing the bars together is kept comparatively low so as not to decrease the resistance at the contact between the bars. When the welding temperature is attained the current is switched off and the force is increased sufficiently to bring about union of the bars. The machines used for this process are frequently semi-automatic, the heating time and the forces pressing the bars together being controlled by the mechanism

of the machine. This control may give either (*a*) a definite welding time, or (*b*) a definite welding current, or (*c*) a definite quantity of energy per weld. The voltage applied across the clamps is a low one, from 2 to 6 volts, and the current is usually alternating. If the bars being joined are different in cross-section the amounts they project from their clamps may have to be adjusted so as to modify the heat losses and ensure both bars being brought to the welding temperature simultaneously. This process is being used for welding such things as steel rails whose cross-sectional area is as much as 10 sq. in.

Flash Welding. This is somewhat similar to butt welding, the chief difference being that the current is switched on before the edges of the plates, or the ends of the bars, being joined come into contact. An arc therefore strikes between those edges as soon as they make contact, and they become molten. Sometimes the edges are brought into contact and then separated in order to establish the arc, which is maintained, despite the ejection of burning metal, by moving the plates together. After the arc has been maintained for some seconds the current is cut off and the plates are moved together so as to bring about the actual weld and this generally upsets the edges of the plates somewhat and produces a flash on each side. The process is used in the motor industry for the welding of the several portions of car bodies together; the machines used for this purpose are comparatively costly and specialised and they are used only in large quantity production schemes. The process is, however, fairly widely used for joining bars and may be thought of as a variation of the butt welding process.

Spot-Welding. This is very similar to butt-welding but is used to join sheet material using a lap joint. It is done in special machines, one being indicated diagrammatically in Fig. 112. The overlapping edges of the sheets being joined are placed between the water-cooled electrodes A and B of the machine and, on depressing the pedal E, the upper electrode is pressed down on to the plates by means of compressed air acting in the cylinder F; simultaneously the current is switched on and passes from one electrode to the other through the plates. The latter are thus heated up in the region of the electrodes and, when they have reached welding temperature, the force pressing the electrodes together is increased and union of the plates occurs at a spot, the size of which will depend on the size of the electrodes, the magnitude of the current, and other factors. The plates are then moved along a little and a second spot weld is produced, the process being repeated as often as may be

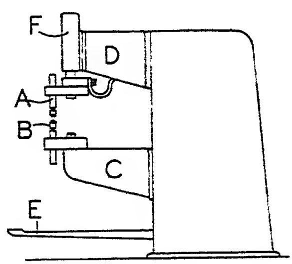

FIG. 112.

required. The spots may be made to overlap so as to produce a continuous joint or may be separated by any specified distance. The machines are usually semi-automatic, the initial and final pressures and the heating time being controlled by the mechanism of the machine. Since the heating times are very short, ranging from $\frac{1}{50}$ up to 2 or 3 seconds, the time control is commonly done by purely electrical means and the times are measured in terms of so many cycles of the (A.C.) mains supplying the current. In the *Sciaky* machines the initial pressure is high and the current low at first, the current is then increased and the pressure reduced, finally the current is switched off and the pressure is again increased.

Satisfactory spot welding machines for plates up to $1\frac{1}{4}$ in. in thickness have been produced.

In a *multiple spot weld* a number of spot welds are produced simultaneously by using multiple contacts connected in parallel. In *duplex spot welding* two pairs of electrodes and two transformers, connected in series, are used to give two welds simultaneously.

Projection Welding. This is similar to spot welding, but whereas in the latter the localisation of heating is brought about by using electrodes of small area, in the former this localisation is due to the formation of one or both of the plates, as indicated in Fig. 113, and the electrodes are comparatively large. This type of welding enables plates of different thicknesses to be joined together more easily than by spot welding.

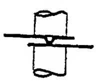

FIG. 113.

Seam Welding. This also is similar to spot welding but the electrodes are replaced by rollers which are pressed together with a suitable force. One roller (or both) is driven by an electric motor so that the plates are moved between the rollers at a suitable speed and the current through the rollers is intermittent, the ratio of the durations of the "on" and "off" periods ranging from 1 : 1 to 1 : 10. Sometimes the current is merely "modulated" so that it varies from a maximum to a minimum value instead of being switched off and on. The roller speed is usually such as to give about ten spot welds per inch and a continuous seam results. The process is more restricted to special purposes than are spot welding and projection welding.

Gas Welding. In gas welding processes the edges of the parts being joined are made molten by playing a gas flame on them; additional metal is usually provided by simultaneously melting a "filler" rod and the union between the plates is completed when the molten metal resolidifies. The various processes used are all essentially the same but may be grouped according to the gases used; these are *oxygen* and *acetylene*, *coal gas*, *hydrogen*, and other gases, often hydrocarbons. The oxy-acetylene process is by far the most widely used and the gases are generally obtained,

from the producers, in steel bottles under several atmospheres pressure; the acetylene is dissolved in a solvent, usually acetone, to eliminate explosion risks. Sometimes an acetylene generator situated close to the welding site is used to produce acetylene, at low pressure, from calcium carbide and water.

Whatever the gases, they are used in a blow-pipe which is provided with control valves to regulate their flow and to enable the desired type of flame to be obtained. The blow-pipes are provided with interchangeable nozzles or tips of different sizes so that small and large flames may be obtained. The consumption of acetylene ranges from about 1 cu. ft. per hour with the smallest nozzle up to 200 cu. ft. per hour with the largest, and the size or " power " of a nozzle is frequently designated by its normal consumption rates; the gas pressure at the blow-pipe varies from 2 up to 8 lb. per sq. in. A typical blow-pipe is shown in Fig. 114. In use the acetylene is turned on first and the gas is ignited, the oxygen

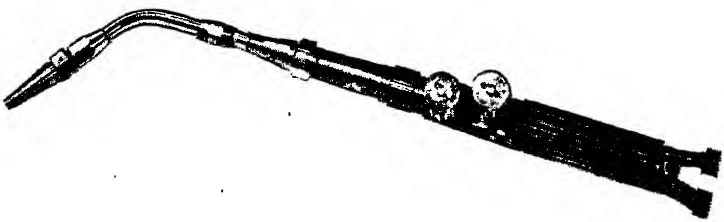

FIG. 114.

valve is then opened gradually until the desired flame is obtained. The flame alters slightly as the nozzle heats up so the final adjustment cannot be made until a minute or two after lighting up. Excess of acetylene gives a *carburising* or *reducing flame* which is highly luminous throughout, while excess of oxygen gives an *oxidising flame* which is characterised by a large luminous cone. A correctly adjusted *neutral flame* has a small luminous cone which is very clearly defined. In the neutral flame, which is the one mostly used, the highest temperature occurs at the tip of the small luminous cone and in use this tip is kept between $\frac{1}{16}$ and $\frac{1}{8}$ of an inch away from the surface of the metal being melted.

The technique of welding can, of course, be learnt satisfactorily only by actual practical instruction and considerable practice, but its salient points will be briefly considered.

Fusion Welding Technique. There are two methods of welding by means of the oxy-acetylene blow-pipe. In *leftward* or *forward* welding the blow-pipe is held at an angle of 60–70 degrees to the job and welding proceeds from right to left as indicated in Fig. 115 *a*; the flame is thus directed towards the open or uncompleted part of the joint. In *rightward* or *backward* or *backhand* welding the flame is directed towards the

completed part of the joint and welding proceeds from left to right as in Fig. 115 *b*. The leftward technique is most suitable for thin material (up to about $\frac{3}{16}$ in.) and for all non-ferous metals, while the rightward

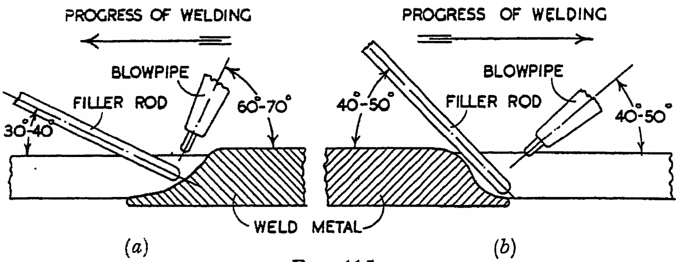

FIG. 115.

technique is best for thick ferrous materials, its advantages being that it is quicker, more economical of filler rod, and produces sounder welds. The enhanced soundness of the weld is largely because the flame plays on the deposited metal to a great extent and thus reduces the rate of its cooling; this allows slag and gases longer to separate out and also reduces the liability to cracking of the deposit. In leftward welding the blow-pipe is given a definite oscillatory motion as indicated in Fig. 116, but for rightward welding this motion is either very slight or is absent; the filler rod is given a circular motion. The oxy-acetylene process, particularly with the rightward technique, has been found to give very homogeneous welds comparable with those produced by the atomic hydrogen process (see p. 144) and superior to ordinary arc welds (see p. 139).


FIG. 116.

The diameter of filler rod must be properly related to the thickness of plate being welded and the size of blow-pipe being used. Too small a filler rod will melt before the edges of the plates have become molten and this will result in a defect known as "adhesion"—the weld metal merely sticking to the parent metal instead of being properly fused to it. Too large a filler rod will melt too slowly and cool the molten pool too much; this causes too rapid solidification and makes the top and bottom beads too small. The expressions given below indicate the proper sizes of filler rod and blow-pipe:

$D=\frac{1}{2}T+\frac{1}{32}$ in. for bevelled plates;
$D=\frac{1}{2}T$ for unbevelled plates;
$P=90T+8$

where D=diameter of filler rod and T= thickness of plate in inches, while P="power" of the blow-pipe in cubic feet of acetylene per hour.

The filler rods used for mild steel plates are commonly mild steel, but for high carbon and alloy steels special rods are used; these will be considered later. It may be noted, however, that the rods for acetylene

welding are different from those used for arc welding ; for example, it is important that ferrous oxide should not be present in the rod as it causes splashing during the welding, also oxy-acetylene rods usually contain silicon and manganese to enable any iron oxide in the weld metal to be eliminated by conversion to iron-manganese-silicate ; the slag thus produced also helps in the control of the molten pool of metal in the weld by increasing its surface tension.

The oxy-acetylene process gives a very low nitrogen absorption by the weld metal (0·02 per cent as compared with 0·2 per cent in unshielded arc welds) and this is an advantage since excess of nitrogen results in brittleness. The process is also particularly suitable for thin plates but can be, and is, used for thick ones also.

In recent years the use of a double-flame blow-pipe, an example of which is shown in Fig. 117, has become fairly common ; the leading

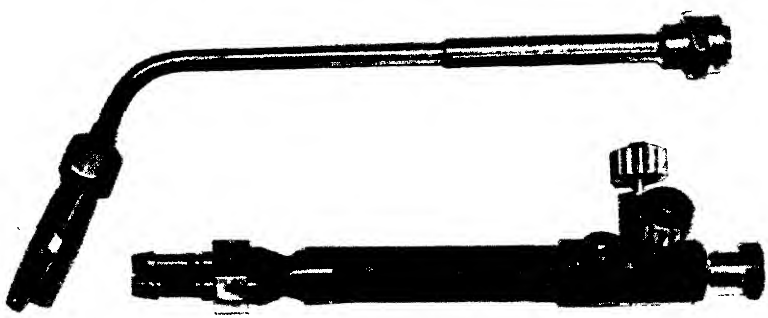

Fig. 117.

pre-heating) flame is adjusted to have an excess of acetylene so as to give a carburising flame and this avoids any oxidation of the plates while the carbon absorption that occurs lowers the melting point of the metal and enables a comparatively small welding flame to be used. Contraction and distortion difficulties are thereby reduced and the speed of welding is increased.

Arc Welding. In arc welding, the heat required to melt the parts being joined is obtained by striking an arc between an electrode and those parts. Both direct and alternating currents are used but direct current is the commoner. Two kinds of electrode are used: (*a*) *carbon*, and (*b*) *metal*, and the latter may be (1) *bare*, (2) *coated*, or (3) *cored*. The metal electrode is by far the most widely used, the carbon arc process being now chiefly confined to certain automatic welding machines and for welds that require no filler metal. In direct current welding the electrode is usually made the negative pole and the work positive, because with a carbon electrode the electrode consumption is less and with a metal electrode the heat developed at the anode (the positive pole) is

greater than at the cathode (the negative pole). The choice of polarity, however, depends on many factors; most coated electrodes weld better when connected to the positive pole; rods containing more than about 0·9 per cent of manganese also generally behave better when the rod is made positive. Reversed polarity (rod positive) is also best for aluminium because it gives better control of the penetration on account of the lower temperature of the plate. The voltage applied across the arc ranges from 18 to 30 with metal electrodes and from 80 to 100 with carbon electrodes; it varies with the length of arc, and the current and the rate of deposition will vary accordingly. Some of the acquired skill of a good operator is directed to maintaining the arc length constant. The currents employed range from 20 to 300 amperes with hand-operated arcs but may be as high as 1,200 amperes in automatic welding machines. With metal electrodes the rate of deposition is roughly proportional to the current employed. Metal electrodes vary between $\frac{1}{16}$ and $\frac{3}{8}$ in. in diameter and are usually from 12 to 18 in. long, while carbon electrodes are usually 12 in. long and range from $\frac{5}{32}$ to 1 in. diameter. The remainder of this section is restricted to metal arc welding.

The current used must be related to the size of electrode and the nature of the work being done. Too low a current is likely to result in poor penetration, the electrode being melted and merely dropped on the job, which is not properly fused. Too high a current results in overheating of the electrode and a poor weld; it also causes excessive spattering and waste of electrode. Nevertheless it is better to use too high than too low a current. With coated electrodes too high a current tends to prevent the slag from covering and protecting the weld deposit, while too low a current produces a viscous slag and increases the risk of slag inclusions in the weld metal. Some idea of the currents used is given by the following table:

Gauge of electrode	*Current, amps.*
12	80–110
10	110–140
8	130–170
6	160–240
4	180–280

In general the largest practicable electrode will give the cheapest weld, but it is difficult to use large electrodes for the first runs of a multi-layer butt weld (see p. 143) because of the restriction of space at the bottom of the gap between the plates being joined.

With bare electrodes the metal is transferred from the electrode to the weld in the form of comparatively large globules which tend to short-circuit the arc, but with coated electrodes the globules are much smaller, the arc is not shorted, and is therefore maintained more easily in a steady state; this is one of the advantages of coated electrodes. Bare electrodes do not usually give such sound welds as coated electrodes; porosity, and

oxide and nitrogen inclusion, being greater, also, they cannot be used satisfactorily with alternating current.

Coated electrodes may be divided into three classes: (1) *Lightly coated* or *washed*; (2) *Semi-coated*; and (3) *Heavy coated.* In semi-coated electrodes the coating forms 2–3 per cent of the total weight, while in heavy coated ones it forms 10 per cent or more. The coatings have two main functions: (*a*) They steady the arc, and (*b*) They help to improve the composition and structure of the deposit. The improvement in the deposit is brought about in several ways: firstly the coating melts rather more slowly than the rod and thus forms a protruding sheath round the end of the rod; secondly, the coating may vaporise and form a blanket of gas round the arc and over the deposit; and, thirdly, the coating forms a slag on top of the deposit. All these actions prevent or reduce the oxidation of the weld metal and also its contamination by nitrogen. In addition the layer of slag reduces the rate of cooling of the deposit and helps to eliminate brittleness and cracking. The stabilisation of the arc is due chiefly to the blanket of gas formed round it, but it has been found that the presence of certain substances in the coating, even in quite small amounts, has a marked effect in promoting stability. The slag produced by the coating is sometimes non-reactive, that is, it has no chemical effect on the deposit but sometimes it is reactive and affects the composition of the deposit by direct action with it. Coatings sometimes contain alloying elements designed to modify the composition of the deposit, but this is not generally considered good practice as different operators achieve more variable results than when the alloying elements are in, or are deposited on the surface of, the rod itself.

Cored electrodes, as the name implies, are hollow and contain non-metallic materials which serve to stabilise the arc and to protect the weld deposit from contamination. They were developed, and are chiefly used, in Germany. It is claimed that they give welds equal to those produced with any coated electrode except the gaseous shield type, to require only two-thirds of the electrical energy per pound of deposited metal required with coated electrodes, and to enable more rapid and cheaper welding to be done.

Arc Welding Technique. The electrode is held at an angle of 60–75 degrees with the line of weld and rightward welding is usual. A "weaving" motion as indicated in Fig. 118 is commonly given to the electrode but is not always necessary and is sometimes definitely detrimental and therefore prohibited. In overhead welds the electrode angle is rather larger, being commonly between 60 and 90 degrees.

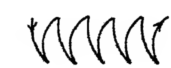

FIG. 118.

Welding Positions. Four welding positions are possible and these are indicated in Fig. 119 where the chain dotted outlines indicate the

limiting inclinations of the job being welded. The easiest to make is the underhand weld and the most difficult the overhead weld, and so the latter is avoided so far as possible. In well equipped welding shops

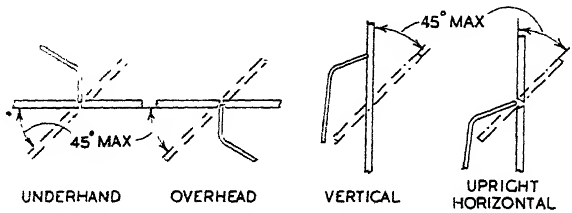

FIG. 119.

" manipulators " are provided so as to enable most, if not all, the welding to be done in the underhand position. The work is bolted to the table of the manipulator, which can then be operated so as to bring the weld into the desired position.

Preparation of Joints for Welding. Thin plates, of about 18 gauge or lighter, may have their edges turned up as indicated at *a* in Fig. 120

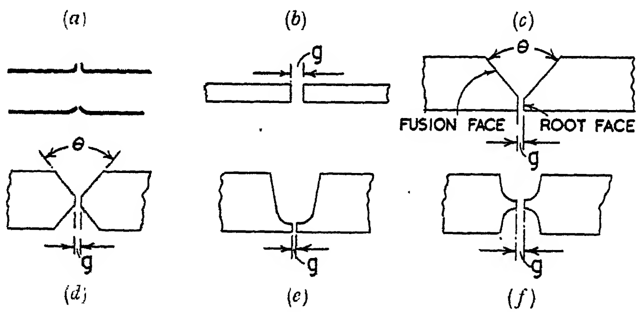

FIG. 120.

and then no filler rod need be used. Thicker plates, up to about $\frac{3}{16}$ to $\frac{1}{4}$ in., can be left square as at *b*, but plates thicker than that must have their edges prepared in one of the ways indicated in Fig. 120 *c–f*. This can be done in the case of the simple bevel shapes either by machining or by oxy-acetylene cutting, but the U preparation must be machined.[1] The preparations *c–f* are known respectively as Single V, Double V, Single U, and Double U and they are all used for butt welds, that is, for joining plates edge to edge. The angle θ is usually between 60 and 90 degrees. The smaller the angle the less the amount of filler rod or electrode required to fill the gap and the quicker the welding, but small

[1] Special blowpipes are now made by means of which the U-plate preparation can be obtained by a process akin to oxy-acetylene cutting.

angles make it difficult to get the weld to penetrate completely to the underside of the plate, increase the difficulty of keeping slag out of the weld, and may thus be the cause of poor welds. Oxy-acetylene welding usually requires rather bigger angles than arc welding does and one advantage of the rightward technique, as opposed to the leftward, is that it makes it possible to use smaller joint angles. The width of the gap *g* left between the plates is also of some importance; too wide a gap allows the molten metal to fall through and makes welding difficult, while too narrow a gap makes the penetration of the weld poor. The gap is usually about $\frac{1}{16}$ in. with thin plates, increasing up to about $\frac{3}{16}$ in. with plates 2 in. thick. The size of this gap and the angles and dimensions of plate preparation for metal arc welds are laid down in B.S.S. 538—1940, and for oxy-acetylene welding in B.S.S. 693—1940. *Fillet welds* are used to join plates at right angles, and in the lap welding of plates, as indicated in Fig. 121. For these joints the plates require no preparation. The choice of type of joint and of plate preparation must take into account the nature of the load on the joint and must balance the costs of plate preparation, filler rod, and welding time so as to produce the lowest total cost.

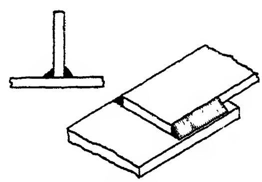

FIG. 121.

It is not generally satisfactory to deposit a layer of metal greater than about $\frac{3}{16}$ in. thick in one run, except in automatic machines, and so for plates thicker than about that amount the weld has to be built up of a number of layers or " runs " as shown in Fig. 122. Even in thin plates

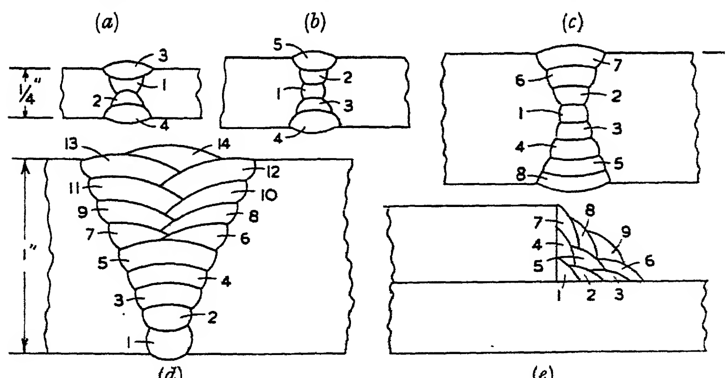

FIG. 122.

that can be welded with a single run a " back run " may be specified in order to ensure a sounder joint. It will be noticed that for a plate 1 in. thick the single V preparation requires fourteen separate runs, while the double V requires only eight. In the former it is not practicable to

carry the sixth and following runs right across the joint because the slag would tend to solidify at one side while the other side was being operated on and slag inclusions and an unsound weld would result. In these mutli-layer welds the surface of each layer should not be more than slightly convex otherwise there will be a tendency for slag to be trapped at the low corners ; a flat or concave surface can be obtained by pausing slightly at each side of the run during the weaving motion, but no pause should be made at the inner sides of runs 6–14 in Fig. 122 *d*. The sizes of runs are usually specified by giving the length of the run to be laid down per electrode and the gauge of the electrode must, of course, be given ; thus a 10/6 run is one made with a No. 10 gauge electrode in such a manner that each (18 in.) electrode lays down 6 in. of deposit ; this figure allows for a discard of about $1\frac{1}{2}$ in. from each electrode.

Multi-layer welds have the advantage that each succeeding layer refines the structure of the preceding one and thus makes the weld as a whole more ductile.

Atomic Hydrogen Welding. In this process a stream of hydrogen is passed through an arc that is struck between two tungsten electrodes, with the result that it is dissociated into its constitutent atoms. As the hydrogen atoms pass away from the region of the arc they reform into molecules and the energy that was absorbed in splitting the molecules originally is evolved as heat ; this heat brings about fusion of the metal being welded. The hydrogen molecules subsequently combine with the oxygen of the atmosphere to produce water vapour and a small amount of heat is evolved thereby, a fan-shaped flame being formed. The principal advantages of the process are the almost complete elimination of contamination of the weld by the atmosphere, and sounder and more ductile welds, due partly to the comparatively slow cooling of the weld metal consequent on the liberation of heat in the outermost regions where the hydrogen combines with oxygen. The process is particularly successful on thin plates and on corrosion-resistant materials and can be performed by hand or in automatic machines.

Automatic Welding Machines. While the majority of arc welding is, probably, done manually quite a large amount is done in semi-automatic machines. These consist essentially of a head that is capable of travelling, at different rates, along the line of the required weld and which carries some form of feeding mechanism to feed the electrode and maintain the arc. The electrode is usually in the form of a continuous coil and the feeding mechanism is a small electric motor. Means of supporting and clamping the work are invariably incorporated in the machine. When the weld is circular the electrode head is usually stationary and the work is rotated underneath it. The electrode feeding motor is controlled by relay systems operated by the voltage across the arc and electro-magnetic means for stabilising the arc are commonly

employed. The welding current is conducted to the electrode by brushes or rollers that make contact with the electrode a few inches away from the arc and bare electrodes have consequently hitherto been essential. Recently, however, satisfactory methods of feeding current to covered electrodes have been developed ; one is to employ a small milling cutter to form a slit through the coating and thus enable a roller to make contact with the metal of the electrode. In another machine a bare electrode is used but a coating, made in strip form, is automatically wrapped on to it just above the arc. Welding machines enable the speed of welding to be increased, thus a current of 600 amperes can be used with a bare No. 12 S.W.G. electrode in a machine as compared with about 100 amperes with manual operation ; they also produce more uniform and consistent welds. Such welding machines can, however, generally be profitably employed only when fairly large quantities of an article have to be welded. In a recently developed process known as the *Unionmelt*, the speed of welding is greatly increased by feeding granular filler material to the weld ; this enables higher currents to be used than are practicable with ordinary metallic arcs and it is claimed that plates up to 3 in. thick can be welded in one pass at speeds ranging from 80 down to 3 in. per minute.

Contraction Stresses and Distortion. If a heated bar is clamped in rigid vices at each end and allowed to cool down, a tensile stress will be set up in it whose magnitude will depend on the temperature range through which the bar is cooled and on the coefficient of expansion of the material of the bar. Similarly if two plates are rigidly clamped and are then welded together a tensile stress will be set up in the plates and weld and may be of sufficient magnitude to fracture the weld metal. If the plates had not been clamped then no stresses, except purely local ones, would have been set up. Hence it follows that, in general, two parts that are being welded together should be left quite free during the process ; this, however, is not always possible. For example, Fig. 123 shows a frame which is built up of a number of comparatively rigid plates A welded to plates B and C which are themselves welded together at D. If the plates B and C were separately welded to A, it would be found practically impossible to make the weld at D, but if B and C are first welded together at D and are then welded at each end to A the job becomes quite straightforward. If two plates are welded together with a butt joint with single V preparation, then when they have cooled down after welding they will generally not be flat but as shown in Fig. 124 *a*. This distortion can be obviated by starting with the plates in the position shown in Fig. 124 *a* which can be done by raising the plate edges on packing rods as indicated. A " back bead " or run also will generally

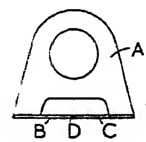

FIG. 123.

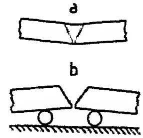

FIG. 124.

bring the plates back into the flat. Such contraction stresses and distortion troubles are sometimes very difficult to circumvent in welding jobs. Internal stresses can generally be eliminated by heating the welded article to a temperature of about 290–300° C., but this is often impracticable. Local heating of the region of the weld also assists in eliminating stresses. However, prevention is better than any cure in this matter and every effort should be made to reduce the stresses set up and the distortion produced to the minimum, and to this end the following points should be borne in mind: (1) The size of the electrode and the current used should be carefully considered; generally speaking, a small electrode and its correspondingly low current will produce less heating and distortion than a large electrode, but as regards internal stresses it has been found that while the small electrode gives the lowest stresses in the *plate* the large electrode gives the lowest stresses in the weld itself. (2) The use of rigid jigs for holding parts to be welded should be confined to "tack" welding of the parts, which should be removed from the jig for the actual welding. (3) The order in which different parts are welded into the complete structure should be carefully considered and, as far as possible, the most rigid members should be welded in first and the more flexible ones last; the order should also be such that contraction is free to take place as long as possible and only the last welds should involve the joining of parts that are not free to move. (4) Pre-heating the job generally helps in the avoidance of internal stress and distortion. (5) For long continuous welds the "step-back" technique is helpful; supposing A, B, C, etc., to be equidistant points along the line of the weld, then welding proceeds from A to B, then from C to B, then from D to C, and so on. (6) The speed of welding is important because an unduly low speed means excessive heating and consequent distortion.

The Inspection of Welds. This is a difficult matter and present methods leave a good deal to be desired in many cases. The methods that are available or which have been tried are: (*a*) Visual, (*b*) Acoustic, (*c*) Magnetic, (*d*) Electrical, and (*e*) by X-ray, and radium, shadow-photography. All welds are subjected to visual inspection and by this means many defects can be detected; for example, undercutting, surface porosity, and badly burnt metal. The actual dimensions of fillet welds can also be checked by means of gauges. Nevertheless a weld that looks quite sound externally can be defective because of internal faults, porosity, slag inclusions, cracks, etc. Acoustic, magnetic and electrical inspection methods have not, up to the present, proved very satisfactory. X-ray and radium photography are undoubtedly the most satisfactory methods at present available but involve the use of expensive equipment, which is rather slow in use, and the interpretation of the photographs obtained calls for considerable experience. The method is, however, gradually being adopted in engineering works for an ever widening range of work;

for certain work, such as important pressure vessels, it is compulsory. X-ray inspection of fillet welds offers greater difficulties than butt welds do and corners are also difficult to deal with.

At the present time the quality of welds in manufacturing practice is maintained very largely by indirect means. Great attention is given to the conditions under which operators have to work and every effort is made to enable as much welding as possible to be done in the underhand position. Extensive trials are made to determine the best electrodes for particular jobs. Operators are also tested at intervals by making them do test jobs that are subsequently subjected to tensile, bend, and impact tests and to microscopical and chemical examination. In America electric arc welds are checked to some extent, as regards quality, by means of an instrument (the Ronay "Arconograph") which produces a permanent record of the variation in the voltage across the arc during the progress of welding, it having been found that that voltage is related to the quality of the weld. (See *Proc. I.A.E.*, May, 1939.)

The Welding Properties of Different Materials. It can safely be said that there is little difficulty in obtaining satisfactory welds in mild steel, and in carbon steels whose carbon content does not exceed 0·3 per cent, with any process, unless the material being welded is in the form of very thin sheets; in the latter case the oxy-acetylene and atomic hydrogen processes are satisfactory but the arc process is not. The difficulty of welding increases with the carbon content of the material and when this is greater than about 0·8 per cent welding is very difficult. This is partly because the deposited metal, particularly with the arc process, is cooled so rapidly by the parent metal that it is, in effect, quenched and the structure is modified accordingly. Some alleviation is obtained by pre-heating the job and this frequently overcomes the difficulty.

Alloy steels also are frequently difficult to weld, not because the weld metal cannot be given the right composition but because it cannot be given the right structure; in the deposited state it has a coarse ingotic structure and this cannot be refined by heat treatment but only by mechanical work which cannot be done on a weld. Rods of suitable composition are essential to the welding of alloy steels. Generally speaking the rod will have approximately the same composition as the parent metal except that some elements will be present in larger percentages, in order to allow for the losses that occur in transferring the metal from the rod to the weld, and the carbon content may be lower.

The corrosion-resistant materials are sometimes difficult to weld and, generally speaking, better results can be obtained from the oxy-acetylene and atomic hydrogen processes than from the arc process. The medium chromium steels suffer from inter-crystalline corrosion after being heated between the limits 500°–900° C. and some metal, generally at a distance

of an inch or so from the weld, is necessarily heated within that range. This effect can be greatly reduced, if not entirely eliminated, by the introduction of small amounts of titanium and tungsten into the material. Chromium tends to form a highly stable slag (Cr_2O_3) and special fluxes are included in the electrode coatings to deal with it. There is also a loss of chromium between rod and weld, and a rod with an increased chromium content is often used; for example, 19·5 per cent Cr rod on 18 per cent Cr work. Very little loss occurs with the oxy-acetylene and atomic hydrogen processes however, but it is important, with the former, to maintain a neutral flame in order to avoid oxidation and carburisation. The austenitic corrosion-resistant materials are comparatively easy to weld.

All the corrosion-resistant materials are comparatively bad conductors of heat and, sometimes, of electricity and they frequently have comparatively large coefficients of thermal expansion. To allow for these factors the electrodes are usually discarded after about one-third of their length has been consumed and are allowed to cool off before being used again; smaller currents and, in oxy-acetylene welding, smaller nozzles are used than for welding mild steel, otherwise over-heating occurs; pre-heating to 150°–300° C. is also commonly done to reduce contraction troubles.

The nitriding steels and the creep-resisting steels containing molybdenum and vanadium can be welded satisfactorily by the oxy-acetylene and atomic hydrogen processes.

Cast iron is a difficult material to weld, largely because of the rapid cooling of the deposit; pre-heating is practically essential. If pre-heating is not practicable then successful welds can often be obtained by using a Monel metal rod.

Copper can be satisfactorily resistance butt welded and arc welding with coated alloy electrodes is also practicable. Oxy-acetylene welding is regarded as the most satisfactory method *on de-oxidised copper* but is not very reliable on other grades.

It is impossible to weld aluminium by the arc process using bare electrodes but with covered ones it is possible, though somewhat difficult; the electrode is made positive and should be held nearly vertical. Spot welding is quite satisfactory on aluminium but very high currents and very short welding times are necessary. By the oxy-acetylene and atomic hydrogen processes welding of aluminium is, however, fairly easy but a flux is essential and, with the former, a neutral flame or a very slight excess of acetylene is desirable. The fluxes used consist of mixtures of sodium, potassium, and lithium chlorides and fluorides. A pure aluminium rod is found to give good results on sheet material and a 5 per cent silicon rod on castings, while sheet material thicker than about $\frac{3}{8}$ in., and heavy castings, should be pre-heated to about 400° C.

Monel metal and Inconel are comparatively easy to weld by all

Trade name	*Coating*	*B.S.S. 639 class*	*Weld deposit analysis*	*Ultimate strength Tons per sq. in.*	*Per cent elongation on $4\sqrt{A}$*	*Materials for which suitable and remarks*
EA	Extruded highly coated	B	C 0·05, Mn 0·27, Si 0·18	28–32	18	Mild steel. All position welds.
EG	Extruded	A	C 0·06, Mn 0·34, Si 0·12	27–29	30	M.S., C.I., and low alloy steels. All position welds. G.P. electrode.
EHV	,,	A	C 0·08, Mn 0·22, Si 0·07–0·16	27–29	26	M.S., low alloy steels. Primarily for vertical and overhead welding.
RG	Braided	A	C 0·06, Mn 0·41, Si 0·07	27–29	20	M.S., C.I., low alloy steels. All position welds. G.P. electrode.
RK	Fly spun	Special	C 0·09, Mn 0·35, Si 0·17, Cu 0·56	37–40	22	Copper-bearing corrosion resistant steels and most 40 ton tensile steels with C less than 0·3 per cent.
S	Dipped	,,	C 0·05 Mn trace, Si 0·01	24	—	Small-gauge electrode for thin plates.
RA	Braided	A	C 0·05–0·1, Mn 0·4–0·6, Si 0·15	30	30	M.S. heavily coated electrode for use in auto-welding, in coils.
P.250	Extruded	Special	C 0·09, Mn 1·04, Si 0·12	Brinell hardness	250	Hard surfacing with carbon steel.
P.350	,,	,,	C 0·04, Mn 0·6–0·7, Si 0·15, Cr 0·6–0·8.	,,	350	,, ,, ,,
P.450	,,	,,	C 0·10, Mn 12·0, Si 0·5, Ni 4·3		450	Hard surfacing with 12 per cent Mn steel.
P.600	,,	,,	C 0·5, Cr 2·5, W 14·0	,,	600	Hard surfacing with 14 per cent W steel.
C.M.	Fly spun	,,	Cu 28·8, Ni 65	36	31	C.I., where a machinable deposit is required. Monel metal electrode.
S.F.	,,	,,	C 0·1, Si 0·6, Cr 18, W 0·6, Ni 8, Ti 0·3–0·8.			Staybrite, Immaculate, Silver Fox 22.
S.M.	,,	,,	C 0·07–0·1, Si 0·7, Cr 18, Ni 8, Mo 2·5–3·0.			BB.4K Immaculate 3M, Staybrite F.M.B.
S.V.	,,	,,	C 0·1, Cr 25, Ni 15			24–15 Ni-Cr steels. Heat resistant.

Selection of electrodes manufactured by Metropolitan-Vickers Electrical Co., Ltd., Manchester.

processes. With the oxy-acetylene process a flux consisting of boric acid powder is recommended for Monel metal while Inconel needs a special flux. In the arc process the electrode should be made positive and direct current is preferable to alternating current; special coated electrodes are necessary.

The table on p. 149 gives particulars of some of the range of electrodes manufactured by Messrs. Metropolitan-Vickers Electrical Co., Ltd., Manchester, to whom the author is indebted for the information given.

Brazing. Brazing is a method of joining two or more pieces of metal together by means of a very thin film of suitable spelter which is fused and run into the space between the pieces. It differs from welding in that the metal surfaces being joined are not fused. The pieces being joined should fit together fairly closely and the surfaces should be clean and free from grease. The spelter is used in the form of small particles and is placed on and adjacent to the joint; a flux is also similarly placed and then the whole is heated, either by placing it in a muffle type furnace or by means of some form of blow-pipe or fire, until the spelter melts and runs by capillary action in between the pieces being joined. Clearly the process can be used only for joining articles whose melting point is considerably higher than that of the spelter. The compositions of spelters have been considered previously (see Chap. 3). The flux that is used is generally powdered borax and it may be used either as a powder or made up with water into a paste.

Bronze "Welding" This name has been given to a process that has been introduced in the last few years and which is intermediate between brazing and welding. It is similar to brazing in that the parts being joined are not fused during the process and it is similar to welding in that the parts are not fitted together closely and considerable filler metal is used. The filler metal, as in oxy-acetylene welding, is in the form of a rod and is fused by means of an oxy-acetylene flame that is played more on the filler rod than on the articles being joined. Fluxes are necessary. The process can be used for both ferrous and non-ferrous materials and is quite satisfactory for cast iron. It can also be used on galvanised articles. The British Oxygen Company market three kinds of filler rod for use with this process. One is a copper-zinc alloy containing silicon and is suitable for joining brasses, bronzes, and copper; the second rod is a copper-zinc-nickel alloy and is intended for malleable iron and steel, while the third rod is a manganese "bronze" and is particularly suitable, because of its great penetrative action, for cast iron. Two special fluxes are also marketed, one for the silicon bronze rod and for the nickel bronze rod on non-ferrous materials, and the other for the nickel bronze rod on ferrous materials. The melting temperatures of these rods vary between 875° and 910° C. The oxy-acetylene flame should be slightly oxidising and this may be judged by the length of the

inner cone of the flame which should be only half the length normal with a neutral flame. The blow-pipe is held at an angle of 30–40 degrees with the work and the leftward technique is used.

Soldering. This is similar to brazing but uses a low melting point alloy solder instead of spelter. The heat necessary for the fusion can be supplied either by warming the articles being joined by means of a flame (the operation being then known as " sweating ") or, more usually, by means of a heated copper soldering " bit." Another method of heating when " sweating " articles is to grip them between two carbon electrodes and to pass an electric current through them, somewhat on the lines of spot welding. A flux is essential for soldering and several kinds are commonly used; for example, zinc chloride (" killed spirits "), resin, tallow, olive oil, etc. Zinc chloride is probably the most widely used flux but has the disadvantage that it is corrosive and if it is not thoroughly removed, after the soldering is completed, causes trouble. Resin is, perhaps, the next most widely used flux, being almost as effective as zinc chloride and non-corrosive. Tallow is used when soldering lead and olive oil for pewter. Aluminium is practically impossible to solder although there are several proprietary fluxes on the market which are claimed to make soldering possible. The compositions and melting temperatures of solders have been considered in Chapter 3.

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Chapter 8

PLASTIC MOULDING

Plastic moulding is a process whereby certain non-metallic substances, now generally called *plastics*, are formed while in the plastic state by pressing them in metal moulds. Plastics may be divided into classes according to the way in which they " set " or become non-plastic. One group, which is called the *Thermoplastic group*, comprises the materials which soften and become plastic when the temperature is raised to a suitable degree and which harden when the temperature falls again. Since the heating process produces little or no chemical change it may be repeated as often as is desired. A second group, called the *Thermo-setting* group, comprises the materials which are plastic at ordinary temperatures or which become plastic when the temperature is raised to a suitable degree, but which harden when the temperature is raised beyond a certain point or is maintained above a certain limit for a suitable time. A third group comprises materials which are hardened or " set " by immersion in a suitable chemical bath.

The chemistry of plastics is by no means simple; it forms a special branch of the subject, one which is developing almost daily and which does not seem likely to approach finality for many years to come. However, this book is not concerned with the chemistry of plastics but with their mechanical and engineering properties and with the engineering aspects of plastic moulding processes.

It is convenient, at this point, to enumerate the more important plastics, grouping them according to the method given above. They are:

Group 1, Thermoplastics	Cellulose-nitrate plastics. Cellulose-acetate plastics. Cellulose-acetate-butyrate plastics. Benzyl-cellulose plastics. Shellac plastics. Vinyl-resin plastics. Acrylic plastics. Polystyrene plastics.
Group 2, Thermosetting plastics.	Bitumen plastics. Phenolic plastics. Urea-formaldehyde plastics.
Group 3.	Casein plastics.

The casein plastics are used chiefly for fancy and domestic articles and are not used for " engineering " purposes; they will not be mentioned further.

The materials listed above are seldom, if ever, used alone but almost always in conjunction with other materials as follows:

(*a*) A *plasticiser* to soften the plastic and make it more easy to mould.
(*b*) A *filler* to give strength, or other properties.

(*c*) Colouring matter.
(*d*) A lubricant to facilitate the flow of the plastic during moulding.
(*e*) A *hardening agent.*
(*f*) An *accelerator* to hasten the action of the hardening agent.

The blending of moulding powders is, however, done by the manufacturers and not by the moulders or, if both operations are performed by one concern, then the processes are carried out in separate parts of the works.

The basic plastic material is generally called the *binder*. With the exception of the filler, the added materials listed above are used in small percentages only, but the filler may amount to as much as 60 per cent of the total weight. Generally speaking the thermoplastic materials, except the shellac plastics, use comparatively small amounts of filler while the thermosetting materials use fairly large amounts. A typical wood-flour filled phenolic plastic moulding powder would have a composition as follows:

Filler	45–50 per cent
Colouring matter	0–5 ,,
Lubricant	$\frac{1}{2}$–$1\frac{1}{2}$,,
Accelerator	0–1 ,,
Binder	Balance

Moulding Methods and Presses. The moulding of thermosetting plastics is done in moulds (such as those described in the following article) in hydraulic or mechanical presses arranged with steam, hot-water, gas, or electrically heated platens. The moulds may be *portable*, in which case they are removed from the press on to a bench for filling and emptying, or they may be *fixed* to the platens of the presses. The moulding cycle for a portable mould will now be described.

A measured quantity of moulding composition, usually in granular form but sometimes consolidated into a pellet, is placed in the lower " force " or half-mould and the mould is assembled and transferred to the press. A comparatively light pressure is first applied and this may be followed immediately by an increased pressure but frequently the mould is opened for a short " breathing " period after the application of the initial pressure. When the mould has remained under the increased pressure for a sufficient time to bring about " curing " of the composition, the mould is removed from the press to the filling bench and the moulding is extracted. The mould is then cleaned by a blast of air and the cycle recommences. Two moulds are commonly used to a single press, one being emptied and recharged while the other is curing. The procedure with the fixed mould is similar, but the mould is not removed from the press. The presses used are of two main kinds, *upstroke* as indicated in Fig. 125 and *downstroke* as in Fig. 126. In what is termed the " double daylight " press an intermediate platen is provided between the upper and lower platens as indicated in dotted lines in Fig. 125. This enables

(*c*) Colouring matter.
(*d*) A lubricant to facilitate the flow of the plastic during moulding.
(*e*) A *hardening agent.*
(*f*) An *accelerator* to hasten the action of the hardening agent.

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two moulds to be pressed at once; one of these may be of the fixed type and the other portable.

In some semi-automatic moulding machines the pressures and curing times are determined by the setting of the machine and in fully automatic

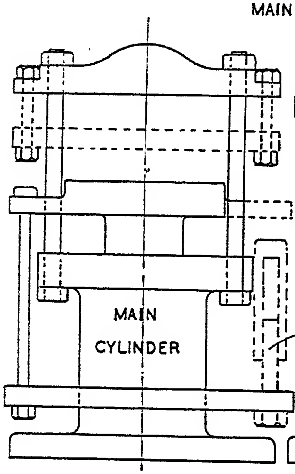

FIG. 125.

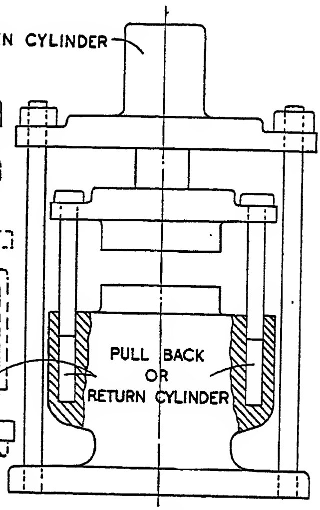

FIG. 126.

machines the charge of moulding composition is weighed out by the machine.

The method of moulding described above is known as *compression moulding.*

Types of Mould. The moulds used in ordinary compression moulding are of three types: (*a*) *Flash*, (*b*) *Positive*, and (*c*) *Positive-flash.*

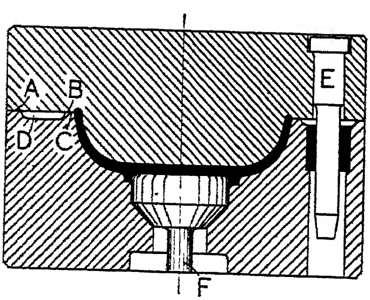

FIG. 127.

The flash type of mould consists of an upper and a lower *force* or die, as shown in Fig. 127. These ultimately butt together at A, by which means the thickness of the article is determined. Any excess of plastic material is extruded between the faces B and C, into the gutter D, thus forming a "flash," or fin, that must be removed in a subsequent operation. Pins E fitting into hardened steel bushes serve to position the top force relatively to the bottom one. An ejector F is provided for the removal of the moulding.

The positive type of mould is shown in Fig. 128. It is characterised by the fact that the whole of the pressure exerted by the press on the forces comes on to the article being moulded, whereas in the flash type of mould a large proportion of the pressure is taken on the flash. The positive mould shown consists of the top and bottom forces, or pistons, A and B and the bolster, or chase, C which, is made slightly less in depth than the sum of the depths of the forces and the thickness of the article. With this kind of mould the charge of moulding material must be carefully controlled, for any excess will make the article oversize, while any deficiency will result (as it would in a flash mould) in a porous article with a bad finish. Shallow grooves D help to prevent scoring and wear due to trapped particles of moulding material.

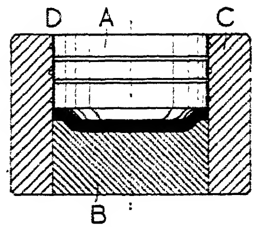

FIG. 128.

The positive-flash type of mould is intermediate between the other two types. The principle is illustrated in Fig. 129. Although provision is made for a flash to occur, the full pressure is exerted on the article as soon as the primary flash has occurred.

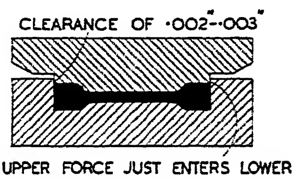

FIG. 129.

The flash mould is generally regarded as the best for quantity production.

With recessed or undercut objects moulds made in several parts may be necessary; commonly a top and bottom force are used in conjunction with a middle portion split into two parts on the vertical centre line, and hydraulic moulding presses fitted with two horizontal rams are made for such moulds.

The vertical surfaces or, more accurately, the surfaces parallel to the direction of withdrawal of the mould, must be given a small amount of "draw"; 0·008–0·020 in. per inch is the usual amount. The heat conduction properties of the mould are also important, the ideal being to obtain a uniform temperature over the whole surface of the impressions in the mould faces; this can be tested by means of wax or low melting-point alloys and can be adjusted by varying the contact areas between the moulds and the press platens. Uneven heating may result in warped articles. The surface finish of the impressions is important, because the plastic materials faithfully reproduce the features of the mould, including quite minute scratches. A high degree of polish is therefore usual on moulds and, after a little use, this finish becomes a high mirror polish. The shrinkage of the plastics on setting and cooling must be borne in mind in the design of moulds.

Injection Moulding. In this process, which has been developed in the last five years or so and which is used chiefly with the thermoplastics, the moulds are kept comparatively cold and the moulding material is heated in external chambers until it is plastic and is then injected into the moulds by means of a plunger. The material quickly cools in the mould which is then opened for the ejection of the article. The process will be seen to bear a great resemblance to pressure die-casting. The adaptation of the injection principle to the thermosetting materials is now proceeding. For articles such as tubes, rods, and sheets an extrusion process can be used.

The Physical Properties of the Plastics. The chief properties that differentiate the numerous plastic materials now available and which make one suitable for one application and another suitable for another are the following. Firstly, the temperature at which the material begins to soften or to char; the thermoplastics soften at temperatures ranging from as low as 70° C. to as high as 180° C., whereas the thermosetting materials do not usually soften very much before they begin to char. Secondly, the ability to obtain the material in any desired colour and shade and the degree of permanence of the colour on exposure to light. Thirdly, the extent to which the material absorbs liquids. Fourthly, the resistance to the action of chemicals and oils. Fifthly, the electrical properties such as specific resistance, power losses, liability to "tracking," etc. Sixthly, the purely mechanical properties such as the tensile, compression, and impact strengths and the modulus of elasticity. The chief plastic materials will now be considered very briefly from these points of view.

Cellulose-nitrate plastic (celluloid) is easily fabricated by heating to between 70° and 110° C. It can be obtained in any colour, but has little strength and is used chiefly for fancy goods where strength is a secondary consideration. Its water absorption is low.

Cellulose-acetate plastic is similar to the cellulose-nitrate material but has greater strength, is better under exposure to light, and is practically non-inflammable. It is, however, more water absorbent. It can be compression moulded at 140°–180° C. and 2,000–5,000 lb. per sq. in. pressure, being cooled under pressure. It can also be injection moulded. The cellulose-acetate-butyrate plastic is very similar to the acetate material but has better weather resisting properties and lower water absorption.

Shellac plastic has good electrical properties and is extensively used for electrical purposes. It can be compression moulded at 120°–135° C. and pressures of 1,000–3,500 lb. per sq. in. It is widely used as an impregnating and binding material and in the form of varnish.

The vinyl-resin plastics are widely used for a variety of purposes. They can be compression moulded at 120°–150° C. and 1,000–4,000 lb. per sq. in. They can be obtained in transparent form and can be bonded

to glass, and are consequently used for making laminated " safety " glass. They can also be used as adhesives by being melted before application or by dissolving them in solvents. They are tough, possess good resistance to chemical action and have low water absorption.

The acrylic plastics may be cast into moulds or may be fabricated by bending and pressing while at a temperature between 80° and 120° C. They possess good dimensional stability and resistance to weather and water, they can be obtained in transparent form, and have a much higher modulus of elasticity (i.e. are more rigid) than most transparent plastics.

Polystyrene plastic is also highly transparent, has good water and chemical resistance, and a low specific gravity. Its dimensional stability and electrical properties are also good. It may be injection moulded at 150°–250° C. and at pressures ranging from 3,000 to 30,000 lb. per sq. in.

All the above materials can be said to be useful for purposes where strength is a secondary consideration, but intrinsically they have comparatively low strengths.

Turning to the thermosetting plastics the bitumen plastic is widely used because it is comparatively low in cost, has good heat and water resisting properties, and fair strength. It requires rather lengthy curing times and is frequently moulded in cold moulds under pressure and cured in ovens after moulding. Cold mouldings shrink more than other types, the shrinkage amounting to as much as 0·025 in. per inch. They cannot, therefore, be held to such close tolerances as the other types. Amongst many uses of bitumen plastics a common one is for battery boxes.

The phenolic plastics (the original Bakelite is one) are probably the most widely used of all the plastics—at any rate for " engineering " purposes, as opposed to fancy articles. This is because they have outstanding properties. They can be obtained with exceptional heat and chemical resisting properties, low water absorption, good dimensional stability, and high mechanical strength ; though the optimum results for all these attributes cannot be obtained simultaneously. The properties depend largely on the filler used. Thus wood-flour gives average properties, asbestor filler gives heat resistance, small flakes or fibres of fabric give high shock strength and mineral fillers give water resistance. The type of filler determines, to a great extent, the ratio of the initial to the finished volume of the material (i.e. what is called the *bulk factor*), this ratio ranging from 2 with wood-flour filler up to 12 with fabric fillers. The mineral fillers are characterised by low contraction on setting ; this ranges from 0·001 to 0·004 in. per inch as compared with 0·005–0·007 in. per inch for wood-flour filled compositions. The phenolic plastics are moulded, usually in hardened steel moulds, at 140°–180° C. and pressures of 2,000–8,000 lb. per sq. in. They require only from 2 or 3 minutes up to 15 minutes to harden, and lend themselves to quantity production. They can give a tensile strength up to 3–4 tons per sq. in. and a crushing

strength up to 20 tons per sq. in., while the elastic modulus (Youngs' modulus) ranges from 300 to 350 tons per sq. in.

The urea-formaldehyde plastics are used chiefly for articles where strength is a secondary consideration. Their one big advantage over the phenolic plastics is that they can be obtained in lighter shades and are more light resistant. They do not flow so easily in the mould, however, and are consequently more difficult to mould in intricate forms. They sometimes give trouble from staining of the mould, which may, in consequence, have to be chromium plated.

Defects in Plastic Mouldings. One defect is failure to take a faithful impression of the mould and this may be due to too low a temperature or pressure or to the use of the wrong moulding composition. Another defect is blistering; this is brought about by the expansion of gases trapped in the material during moulding and can only occur if the moulding is still plastic to some extent when it is removed from the mould. It may be due to incomplete curing or to the omission of the "breathing" period during the moulding cycle and it can also be due to decomposition of the moulding material following over-curing. Another type of defect is porosity; this may be due to the use of too low a moulding pressure, the omission of "breathing," or to bad design of the article. The latter is usually the use of too heavy sections in conjunction with light sections. Another defect is flow marks; these may be due to uneven heating of the mould, to the "breathing" being done too early in the moulding cycle, or to the use of too hot a mould which brings about surface curing of the moulding before the full pressure is applied.

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Chapter 9

CLASSIFICATION OF MACHINE TOOLS. GENERATING AND COPYING PRINCIPLES. ACTION OF CUTTING TOOL WHEN CUTTING

Machine tools are now so numerous in type that it is impossible to describe every separate type in a book of reasonable size; nor is this necessary, since the difference between many of them are merely matters of detail and not of principle. It is possible to classify machine tools into a comparatively small number of basic groups and it will be sufficient to describe, fairly fully, an example of each group and to consider the chief variations within the group in rather less detail. The classification can, however, be done in several ways, although none of them gives absolutely clear-cut groupings.

One possible classification is into three groups—*single-purpose*, *multi-purpose*, and *special*. A single-purpose machine is one that is designed to do one particular kind of operation but which is built more or less as a standard product by a number of machine tool builders. The single-purpose machine is not, however, restricted to one particular job; for example, a shell turning lathe is designed specially for shell turning and is not adapted for general lathe work; it is not, however, restricted to one particular size or profile of shell. Single-purpose machines are generally simple in design and are often little more than standard multi-purpose machines stripped of all the " frills " and simplified as much as possible; they are consequently low in first cost. Unless they can be occupied for a reasonable percentage of their useful life on the job for which they are designed, it would generally be better to use a multi-purpose machine which can do other jobs as well.

A multi-purpose machine tool is one that is capable of doing a number of different types of operation. For example, a sliding, surfacing, and screw-cutting lathe fitted with a taper attachment can do almost every lathe operation except such specialised ones as the relieving of milling cutters and hobs and the turning of non-circular sections. The multi-purpose machine costs more than the single-purpose one, but in most machine shops it can more easily be kept fully occupied and it is consequently the most widely used type. When the number of different operations possible is large, the multi-purpose machine may sometimes be referred to as *universal*.

The special machine tool is one built specially for some particular job that is required in large quantities. It has to be specially designed for that job and is not usually capable of doing any other job, so that it must

be scrapped when the job ceases. It costs more than the single or multi-purpose machines but does the job in less time and thus is able to show a saving in total cost if the number of articles required is sufficiently high.

A second method of classification is according to the kind of cutting tool used, though perhaps it would be more precise to say according to the size of chip removed. This classification gives two groups, namely, machines using " cutting tools " which produce chips visible as such to the unassisted eye and machines using abrasives which produce " chips " so small that they can be recognised only with the aid of a microscope. Until a few years ago the first group could have been defined as machines using steel cutting tools, but cutting tools are now frequently not made of steel.

A third method of classification is according to the type of surface principally produced, e.g. surfaces of revolution ; plane, or ruled surfaces and miscellaneous surfaces. Thus lathes are primarily adapted for producing surfaces of revolution and milling machines for producing ruled surfaces. This method is the least satisfactory of the three methods considered but has some advantages.

A table showing the grouping of the principal machine tools according to the above classification is given in Fig. 130.

			A *Using " cutting tools "*	*B* *Using abrasives*
Machine tools.	Single purpose Multi-purpose Special	1. Producing mainly surfaces of revolution.	Lathes. Boring machines. Drilling machines.	External cylindrical grinder. Internal cylindrical grinder. Honing machines. Lapping machines.
		2. Producing mainly ruled surfaces.	Milling machines. Planing machines. Shaping machines. Slotting machines. Broaching machines.	Surface grinding machines. Spline grinding machines. Lapping machines.
		3. Gear-cutting machines.	Spur-gear cutters. Bevel-gear cutters. Worm-gear cutters.	Spur-gear grinding machines. Worm grinding machines.
		4. Miscellaneous machines.	Thread-milling machines. Cam-milling machines. Die-sinking machines. Sawing and filing machines.	Thread grinding machines. Cam grinding machines. Cutter grinding machines. Die polishing machines.

FIG. 130.

Generating and Copying Principles. All machine tools use both of these principles, the essential difference between which can be illustrated by a simple example. Suppose it is required to draw a circle on a sheet of paper; one way is to use a pair of compasses and this is a generating process; a second method is to obtain a circular disc of cardboard or metal, to place it on the paper, and to trace round it with a pencil; this is a copying process and the accuracy of the result depends *directly* on that of the "former" or "template" that is copied. Perhaps a better example of a generating process is the drawing of an ellipse by means of an "elliptic trammel"; this consists of a straight rod or bar whose ends are guided along two straight slots at right angles to each other and which carries a tracing pencil at some intermediate point. When the ends of the rod are traversed along the slots the pencil will trace out an ellipse, the accuracy of which depends only *indirectly* on the straightness of the slots.

The Action of a Cutting Tool. The precise action of a tool when cutting has not yet been fully investigated, but a considerable amount of research has been carried out in order to try to elucidate the problem. *Nicolson* and *Smith* were among the first to carry out experimental work on the problem and *Rosenhain* and *Sturney* have confirmed and amplified their work. The last-named experimenters in their report to the *Cutting Tools Research Committee* (see *Proc. I. Mech. E.*, January, 1925), have distinguished three types of chip and have given microphotographs of them. They call the types the "tear," "shear," and "flow" types respectively. *Hans Ernst*, in a lecture to the American Society for Metals (see "Machining of Metals," published by the American Society for Metals, 1938), also distinguishes three types of chip which he calls respectively the "discontinuous," "continuous," and "continuous with built up edge" types. The descriptions given in the following paragraphs are based on the work of the above experimenters.

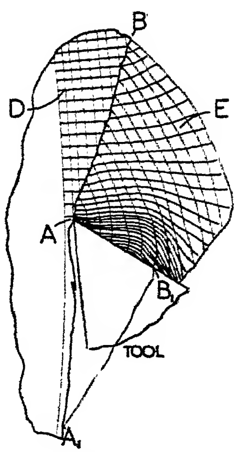

FIG. 131.

Referring to Fig. 131 (which is based on Fig. 12 of Nicolson and Smith's Book "Lathe Design"), the tool is shown cutting the edge of a disc whose face has been ruled with a series of radial and circumferential lines as seen at D. The tool is shown having just removed the metal within the triangular area A_1B_1A and this material, together with that in the area AB_1B, forms the chip E which, having sheared along AB, is now separated from the parent stock D. The tool then begins to act on the inclined face AB of the parent stock, but because

the tool edge, however sharp it may appear to be, is actually rounded, it at first tends to " ride over " the surface of the work and thus to push the tool to the right and the work to the left. Actual measurement of the horizontal force on the tool shows that it gradually increases up to a maximum and then falls off again. The maximum value corresponds to the penetration of the edge of the tool into the material being cut, and as soon as this occurs the material starts to " pile up " on the top face of the tool. This piled up material is severely compressed and distorted and it slips across the face of the tool in a succession of " jerks," each jerk corresponding to the formation of a tear, extending approximately circumferentially from the tip of the tool, which tends to separate the chip from the parent stock. In the early stages the tears do not extend very far, but as more and more material piles up on top of the tool the vertical force on the latter and its reaction on the chip increase, until finally one tear extends up to a point such that the shear strength of the section corresponding to AB is too small to sustain the load and shearing occurs. The chip is then separated from the parent stock and the action begins all over again. The variation of the vertical and horizontal forces on the tool is indicated in Fig. 132. As just described the action is that which occurs only at very low cutting speeds ; at higher speeds there is not time for the full action to take place and the form of chip is modified as indicated in Fig. 133. The tears or shears do not have time to extend right out to the surface of the chip and so successive " chips " may not be completely separated from each other and would sometimes form a continuous ribbon except that as the ribbon curls over it butts up against the surface of the work and the resultant bending action fractures it. The short lengths of " ribbon " produced are, however, full of tears and cracks and are easily broken ; the action is not essentially different from that at slow speed and the chip is not continuous in the sense that *Ernst* uses that term. In the high-speed action there is considerable sliding of the chip ribbon over the face of the tool and the pressure at B (Fig. 131) is high and may produce a tear at A so that the edge of the tool may not be in contact with the chip at all and may serve only to clean up the irregularities of the surface left as the result of the tearing.

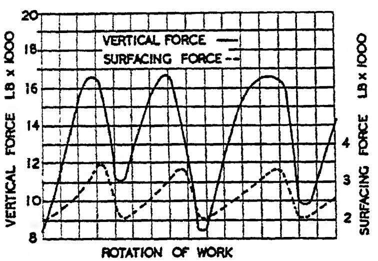

FIG. 132.

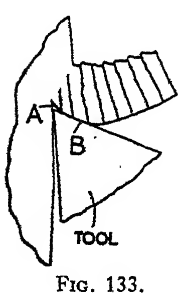

FIG. 133.

In the shear type of chip distinguished by *Rosenhain* and *Sturney*, the action is on the lines of that described above, but the production of tears

is almost absent, so that chip separation is almost entirely due to shearing action along lines similar to AB (Fig. 131).

In the flow type of chip the metal flows by means of continuous plastic deformation and forms a long ribbon which when examined microscopically shows no signs of any tears or other discontinuities.

The "Built-up Edge." If a tool which has been working for some time under fairly arduous conditions of speed and cut is examined, it will frequently be found that at the extreme edge of the tool there is a little pile of material which firmly adheres to the metal of the tool and which can only be removed by the application of considerable force. During the action of the tool this piled up material seems to form a "false" cutting edge to the tool and it is usually referred to as "the built-up edge." The built-up edge appears to be formed by the adherence of the metal of the chip, because of the great pressure, to the face of the tool, followed by rupture and sliding of the chip material over the similar material which has adhered to the face of the tool. According to *Ernst* the built-up edge increases in height until the upper portion becomes unstable and breaks away, the building up process then commencing once more and the cycle being repeated many times per second. In the lecture referred to above he gives microphotographs showing part of the built-up edge adhering to the tool and part to the chip. For further information on this subject the reader is referred to the works listed at the end of Chapter 11 and especially to "Work-Hardening Properties of Metals," by E. G. Herbert, *Trans. A.S.M.E.*, 1926.

Cutting Speeds, Feeds, and Tool Life. Most of the experimental work carried out on cutting tools has not been of the fundamental nature of that mentioned above, but has been more immediately practical in aim and has sought to determine the optimum conditions of cutting speed, depth of cut, feed, tool angles, etc., to give a required tool life. It will be convenient, however, to defer consideration of the results of these researches until somewhat later.

Chapter 10

THE LATHE. METHODS OF HOLDING WORK. TYPES OF TOOL. LATHE OPERATIONS

The lathe is a machine in which work is held so that it can be rotated about an axis while the cutting tool is traversed past the work from one end to the other thereby forming it to the required shape. Clearly any section by a plane perpendicular to the axis of rotation will be circular. The lathe is probably the oldest but is still the most important of all machine tools.

A good example of a modern precision lathe is shown in Fig. 134. It is the Model C No. 10, built by Messrs. Holbrook Machine Tool Co.,

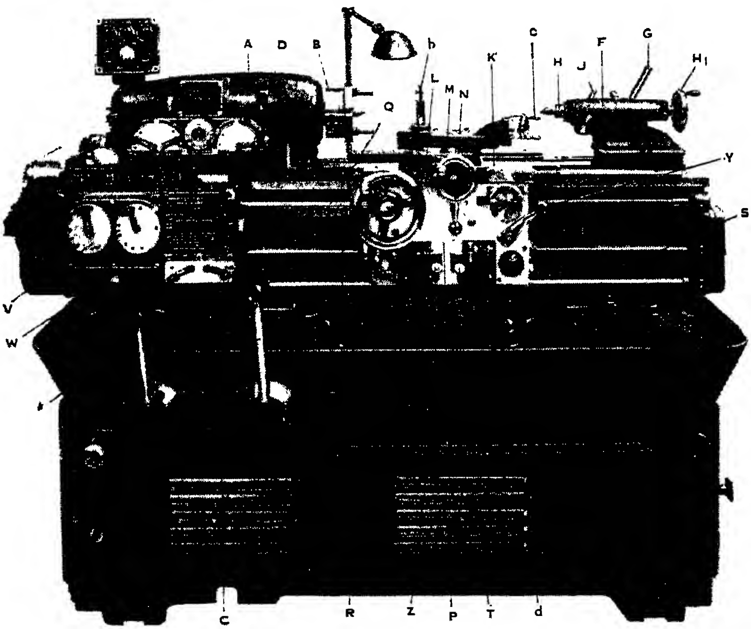

Fig. 134.

Ltd., Stratford, London, to whom the author is indebted for the loan of photographs and for technical information.

The lathe consists essentially of a *bed*, *headstock*, *tailstock*, and *saddle*. The bed is a box casting with machined " ways " or " shears " on its upper surface and is bolted to a heavy base casting which provides a tray to catch any cutting fluid that may be used and also serves to house the driving motor and electrical switch-gear. The headstock A is secured

to the bed and carries the bearings in which the spindle B rotates. These bearings are automatically lubricated by a mechanical pump and are designed to work satisfactorily under the extreme conditions of low speed with heavy cuts and high speeds with light cuts. Twelve different spindle speeds are provided ranging from 23 to 2,000 r.p.m. These speeds are obtained partly by electrical means—the driving motor being a three-speed one—and partly by toothed gearing. One gearbox, providing two speeds, is built integral with the motor unit and is controlled by the lever C, while gearing housed in the headstock and controlled by lever D provides two further changes. The motor speeds are controlled by lever E and the drive up to the spindle is through V belts, the spindle being relieved of the belt pull.

The tailstock F is free to slide along the bed ways but can be locked in any position by the lever G; it carries the " poppet " H which can be adjusted in and out by the handwheel H_1 and a screw. The poppet is locked by lever J.

The saddle K is free to slide along the bed ways and carries the compound slide rest L, M, N while the saddle apron P carries the gearing giving the self-actuating feeds and also the lead-screw nut. The sliding of the saddle along the bed is done by means of a spur pinion carried in bearings in the apron and engaging the rack Q fixed to the bed. The spur pinion can be turned either manually by the handwheel R or mechanically by the feed shaft S, this latter drive being engaged and disengaged by the lever T. The feed shaft S is driven from the headstock spindle through gearboxes V and W which provide a range of feeds from 0·003 up to 0·020 in. per spindle revolution. For screw cutting the saddle is traversed by the lead-screw which, like the feed shaft, is driven from the spindle through the gearboxes V and W. A split nut carried in the apron can be engaged with the lead screw by means of the lever Y which is interlocked with the levers T and Z to prevent the nut being engaged while the feeds are in use.

The compound slide rest consists of the cross-slide L, swivel M, and top slide N. The cross-slide is free to slide across the saddle perpendicular to the bed ways and is operated by a screw either manually by a handwheel or mechanically by the feed shaft, this drive being engaged by the lever Z. A dial, graduated in thousandths of an inch is carried by the cross-slide screw and enables accurate adjustments to be made. Because of backlash between the nut and screw the dial graduations can only be relied on if the adjustment is always made in the same direction, in or out; if the slide is moved just a little too far it must be brought back and then forward again, or vice versa. This remark applies to practically all machine adjustments. The swivel M enables the top slide to be set at any angle from 0 to 90 degrees with the spindle axis. The top slide carries the tool post *b* in which the tool is held and is traversed by a screw that is geared to the handle c.

A lever *d* carried by the apron controls the driving motor switch through a shaft and enables the motor to be stopped, started, or reversed.

The tailstock is made in two parts, the upper portion being adjustable at right angles to the bed ways relatively to the lower part; the two parts can be locked together after adjusting.

Methods of Holding the Work. Several methods are available and the choice of method will depend on the nature of the work itself and of the operation to be performed on it. The most important methods will be dealt with in turn.

1. *Between Centres.* This is a widely used method, particularly in engine lathe work. Centre holes as indicated in Fig. 135 are drilled in

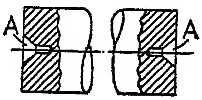

FIG. 135.

the ends of the work by means of special "centre drills" one of which is shown in the figure; the operation may be done in an ordinary drilling machine, in a special centering machine or in the lathe itself. The work is then supported on two "centres," one of which is carried by the lathe spindle and the other by the tailstock poppet. These centres are made of tool steel, hardened and tempered, and the portion A (Fig. 136) is made a standard Morse taper to fit corresponding taper holes in the head-stock spindle and tailstock poppet, an adapter being generally necessary in the first position. The portion B is ground to the proper included angle which is generally 60 degrees but may be 75 degrees. Flats may be provided to enable a spanner to be used to remove the centres. The centre carried by the spindle is called the "live" centre because it rotates; it is sometimes ground true on the surface B while it is in position in the spindle, a small motor-driven grinding wheel being mounted in the tool post for that purpose, it then generally carries a mark to enable it to be put into the spindle always in the same position. The centre carried by the tailstock poppet is called the "dead" centre. Because of the clearance holes (seen in Fig. 135) the work does not bear on the extreme points of the centres; this is important because otherwise the positioning of the work will be uncertain. The size of the centre hole must be suitably proportioned to the weight of the job and the size of cut to be taken. In order to drive the work when it is mounted between centres a "driving carrier" A (Fig. 137) is secured to its left-hand end and this carrier bears against a driving pin B that projects from a driving plate C screwed on to the spindle nose. A driving plate can be seen in position in Fig. 134.

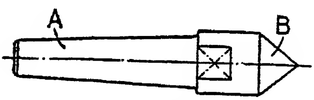

FIG. 136.

This method of holding work has the advantage that the work can be removed from the lathe as often as may be desired and on replacement it will always "run true," that is, it will rotate about the same axis as before. Similarly the work may be transferred from the lathe to, say, a grinding machine and will again run true. The chief drawbacks of the method are that it is impossible to drill a hole up the end of the work; it is not suitable for castings and forgings except very simple ones; and lastly, in order to machine the whole length of a bar the bar must be turned end for end after one end has been machined.

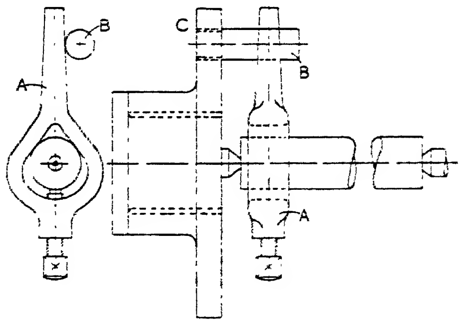

FIG. 137.

The axial adjustment of the tailstock centre must be carefully made, since any slackness will result in untrue work and, possibly, broken tools, while too tight an adjustment will cause the dead centre to run hot and possibly, to seize. The poppet must be readjusted from time to time during the progress of the work in order to take up any slackness due to wear and at the commencement, and at intervals during the progress of the work, a little oil or grease must be applied to the dead centre. For heavy work ball-bearing live centres are frequently used in the tailstock.

2. *On a Mandrel.* The use of a mandrel enables a piece of work that has a hole through its centre to be supported between centres. A mandrel is a bar with centre-holes at each end and whose surface is ground true to those centres. The bar is nearly cylindrical but has a very slight taper and its diameter near to the middle of its length must be equal to that of the hole in the work to be supported on it. The mandrel is driven into the work by means of a lead hammer and friction is relied on to drive the work, the mandrel being driven by a carrier in the ordinary way. Mandrels may be hardened or left soft and are frequently turned up from a piece of bar as required. Clearly the use of a mandrel enables the outside of a piece of work to be turned concentric with the inside and in general such work would have the hole finished first and the outside finished on a mandrel subsequently. An allied method is to grip a piece of bar in a chuck and to turn it so that the work can just be forced on to it; the work is then turned as if it were on a mandrel. Clearly the bar must not be removed from the chuck until all the pieces of work have been machined. The bar may be screwed if it is required to carry work having a screwed hole.

3. *In a Chuck.* This method of holding work is of very great importance since it is almost universal with capstan and turret lathes and automatic

screwing machines and is also widely used with engine lathes. Briefly, a chuck is a vice adapted to be carried on the nose of the lathe spindle. Chucks are of three main types, namely, *independent jaw* chucks, *concentric* or *self-centering* chucks and *collet* chucks. Independent jaw chucks usually have four jaws as shown in Fig. 138 ; the jaws are carried

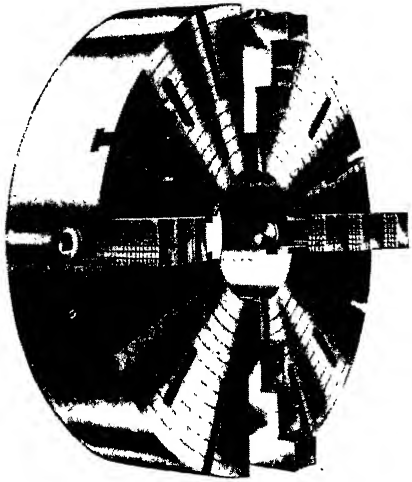

Fig. 138.

in radial slots in the chuck body and can be adjusted in and out independently by means of screws operated by a chuck " key." The body of the chuck is provided with a screwed hole to fit the spindle nose of the lathe. The concentric chuck usually has three jaws as shown in Fig. 139,

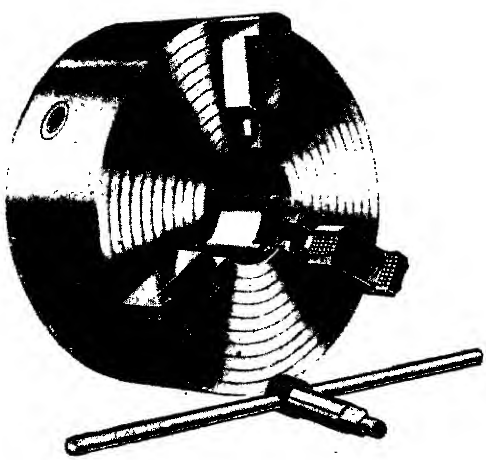

Fig. 139.

and these are all moved in or out together by means of cams, a scroll (this is a disc with a spiral groove cut on it), or other mechanism ; consequently a cylindrical piece of work when held in such a chuck will automatically be centred so that its axis coincides with that of the chuck and thus with the spindle axis. Clearly the concentric chuck is unsuitable (unless special jaws are fitted) for irregular shaped articles ; for these the independent jaw chuck must be used.

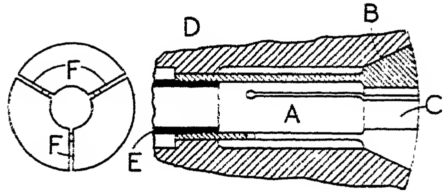

FIG. 140.

The principle of the collet chuck is shown in Fig. 140. The collet proper, A, is a forging whose enlarged end is machined to a cone B that fits a corresponding cone in the lathe spindle. The collet is hollow and at C is machined just a little larger than the diameter of the work to be held. The end D of the collet is screwed to take a tube E which passes down the spindle of the lathe and which has a shoulder that bears against the end of the spindle. The tube E is provided with a handwheel by which it can be rotated, while the collet has a slot that engages a pin projecting from the lathe spindle and which prevents it from turning relative to the spindle. The collet has a number of slots F, usually three, and so by turning the tube E and drawing the collet into the spindle slightly, the end is closed in so as to grip the work. Clearly the variation in diameter of the work that can be gripped by any collet is quite small and so a range, commonly 16, of different sized collets must be provided. Collet chucks are used chiefly for holding bright drawn rods, but by providing suitable jaws on the end of the collet the principle can be adapted to accommodate irregular-shaped articles. Somewhat elaborate mechanisms are used to operate the collet chucks used in turret lathes and automatic machines ; these need not be described here but it may be pointed out that some of them tend to retract the bar slightly as the chuck is closed while others do not. The latter are sometimes called "dead length" chucks.

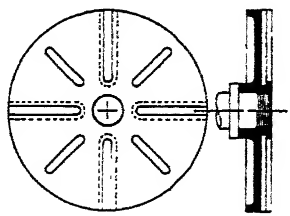
FIG. 141.

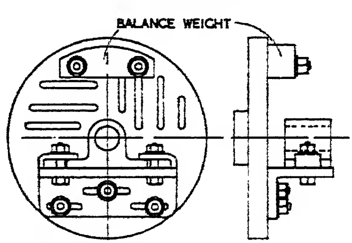

FIG. 142.

4. *On a Faceplate.* A faceplate is a circular casting adapted to screw on to the spindle nose of the lathe and provided, as shown in Fig. 141,

with a large number of holes to take holding down bolts. They are used to hold irregular-shaped articles that cannot be held in chucks, and the articles are packed up on the face of the faceplate by means of packing pieces and are clamped by means of holding down bolts and straps. Angle plates are commonly used in conjunction with faceplates as shown in Fig. 142. When work is mounted on faceplates it is important that the whole mass should be approximately balanced and for this purpose balance weights, as shown, are bolted to the faceplates.

Lathe Tools. The number of shapes and types of lathe tool that have been, and still are, used is very large despite all the efforts that have been made to standardise them and thus reduce their number. Tools may be classified as being either roughing tools or finishing tools according as they are designed to take heavy roughing cuts or light finishing cuts. The differences between the various types of tool are, firstly, differences in shape as seen in plan view, and, secondly, differences in the angles to which the surfaces of the tools are ground; the former are very largely unnecessary and merely reflect the idiosyncrasies of different machine shops, the latter are of more importance and are due to the variety of materials that has to be machined.

The nomenclature that will be used is that employed by the *Lathe Tools Research Committee* and shown in Fig. 143:

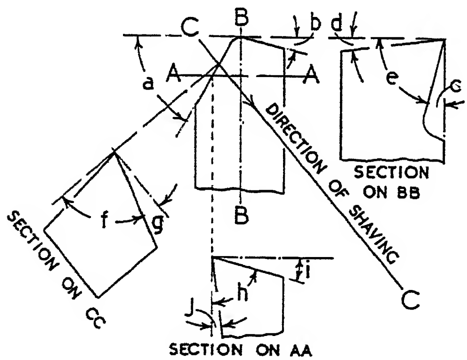

FIG. 143.

a=plan angle.
b=horizontal front clearance.
c=front top rake.
d=front clearance.
e=front cutting angle.
f=true cutting angle.
g=true top rake.
h=side cutting angle.
i=side top rake.
j=side clearance.
r=nose radius.

Front Roughing Tools. These are designed to take heavy cuts and are traversed parallel to the axis of rotation of the work. Some common plan shapes are shown in Fig. 144, the cutting edges being shaded. The shape *a* is characterised by having an entirely curved cutting edge and such tools were widely used at one time, particularly in the United States of America, but are now not so much used. The other shapes all have cutting edges composed of two straight lines joined by an arc and differ in the magnitude of the plan angle. As will be seen later, the 30-degree tool can take cuts at higher speeds than the other shapes but, being very

liable to chatter, is not much used. The 90-degree tool has the advantage that it leaves the shoulder of the work square with the axis and it is widely used. The 60-degree tool represents a compromise between the 30-degree and 90-degree tools and is also widely used. The shape at *e*

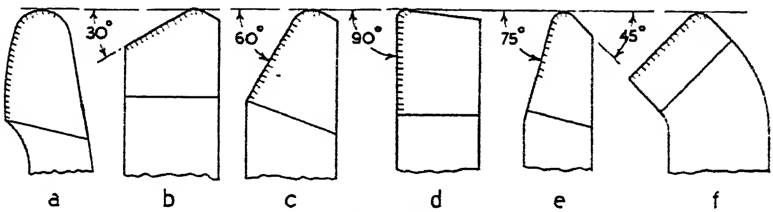

FIG. 144.

is characterised by having a large nose radius and is a compromise between a roughing and a finishing tool. At *f* is shown a cranked tool.

The clearance angles ensure that the tool surfaces do not rub on the work and should be as small as possible consistent with the attainment of that object; the horizontal front clearance is commonly between 6 degrees and 15 degrees but, as the example *e* shows, may be as great as 45 degrees. The front clearance angle is commonly about 12 degrees and the side clearance angle between 6 and 12 degrees. The biggest clearances are used with the more ductile materials. The cutting angle varies more than the other tool angles and may range from as low as 45 degrees to as high as 90 degrees, and may even sometimes be greater than 90 degrees. The best value for the true cutting angle depends on many factors, which are considered later on, but generally speaking it may be said that for the soft, ductile materials of low tensile strength a value of 45–60 degrees will be suitable; for steels of medium strength and hardness the value should be 60–80 degrees; for hard steels of high tensile strength and for cast steels the value should be about 80–85 degrees; and for cast materials, such as cast iron and cast brass, the value should be about 85–90 degrees, though some cast irons can be cut satisfactorily with lower values for the cutting angle. The values just quoted apply to ordinary carbon tool steels and to high speed steels; cemented carbide tools generally have cutting angles somewhat larger than those used for tool steel tools, the top-rakes being about 20–30 per cent less for the carbide tools. The nose radius is sometimes zero but usually is between $\frac{1}{16}$ and $\frac{1}{4}$ in., depending on the size of the tool, i.e. its cross-sectional dimensions.

The "Klopstock" Tool. This is a form of tool in which the top surface, on which the chip impinges, is ground away so as to leave a narrow lip all round the cutting edge. It was developed by Prof. Klopstock as the result of experiments which were later confirmed by large-scale use in machine shops and is described in a paper to the American

Society of Mechanical Engineers, 1925. It is claimed to give increases in life of up to 50 per cent and reductions in power required of 25 per cent, but it does not seem to have been used anywhere except in Germany.

Tools having a groove ground in their upper surfaces as shown on the right in Fig. 145 are, however, used fairly widely both in America and England. Such a groove is commonly referred to as a " chip breaker " and is used generally as such, but its use is said to increase the tool life and to decrease the power required so that it may give a similar action to the Klopstock tool.

Other Types of Lathe Tool. Besides front roughing tools the most important tools are: (1) Side-facing tools; (2) " Knife " tools; (3) Parting-off tools; (4) Screw-cutting tools; and (5) Boring tools. The plan shapes of these are shown in Fig. 145. Finishing tools are

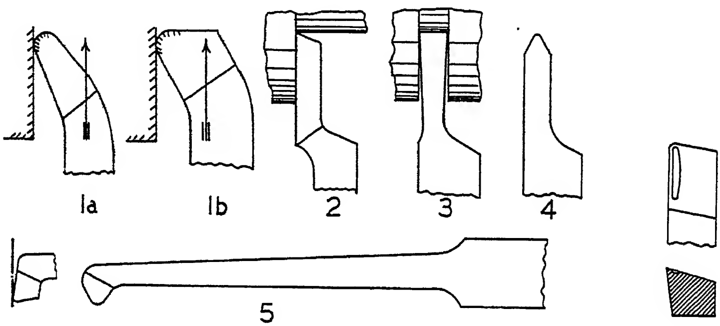

FIG. 145.

commonly similar to roughing tools except that they have smaller nose radii, but there is a tendency nowadays towards the use of tools with an appreciable length of cutting edge that is parallel to the axis of the work

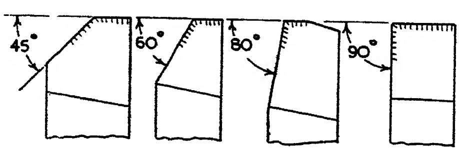

FIG. 146.

as is indicated in Fig. 146. Such tools require very careful setting in the tool post.

Tangential Tools. Lathe tools are sometimes made so that the shank of the tool lies more or less tangential to the work as indicated in

Fig. 147. The chief advantages claimed for such tools are, firstly, that they can be reground many more times than ordinary tools and thus have a very long life and, secondly, that they are more rigid and can take heavier cuts. They require special holders and are used mostly in capstan and turret lathes, for which application they have the advantage that they do not project so far in the horizontal plane and so do not cause difficulties through fouling the cross-slide when the turret is rotated.

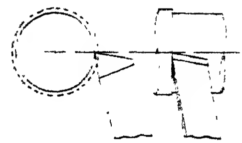

FIG. 147.

Right- and Left-hand Tools. Most lathe tools are made in both right-hand and left-hand forms. Right-hand tools are designed to cut whilst traversing from right to left or, in the case of side tools and knife tools, on the right-hand face of a flange ; they are more widely used than left-hand tools. The latter are " mirror reflections " of the right-hand tools, the mirror being parallel to the axis of the tool shank.

Form Tools. Shapes other than those composed of cylinders and cones of small apex angle are frequently required and are generally obtained by means of form tools made to the required profile so that the work is a direct copy of the tool. Such tools are fed in radially and are not traversed at all. They are of three main types and these are shown in Figs. 148, 149, and 150. That in Fig. 148 is made from a piece of flat tool steel whose edge has been formed to the required profile and which has been suitably backed off to provide a front clearance. The type in Fig. 149 has the profile formed on the face of a block whose back is provided with a dovetail by means of which the tool is held in a suitable holder ; this tool is thus a tangential tool. The cutter shown in Fig. 150 is turned in a lathe by means of a tool of the first type and is then gashed as shown so as to provide a cutting edge. It also has to be held in a special holder. Unless the face A is made radial the shape of the work produced will be different from that of the tool used to produce the cutter, while if it is made radial the tool will have no front clearance ; it is therefore dropped below centre as shown and the shape of the tool is modified so as to produce the shape of work required. The first type of cutter is cheap to make and is used for small quantities, the other two types are much more costly and so are used only for large quantities. Since (with form tools) the total length of cutting edge that engages the work may be very long, the cutting speed usually has to

FIG. 148.

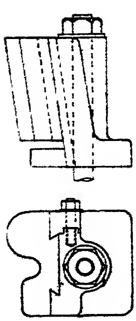

FIG. 149.

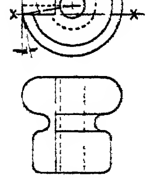

FIG. 150.

be kept quite low in order to avoid chatter and to get a good finish on the work.

Setting of Lathe Tools. It is important that lathe tools should be set with their cutting edges level with the axis of the work, because otherwise the cutting and clearance angles will differ from those intended and the tool will not cut so well, if it cuts at all. The effect of varying the tool setting is shown in Fig. 151. The necessary adjustment is made by

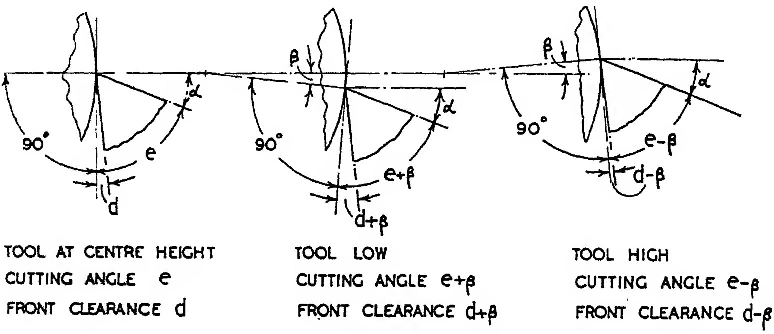

Fig. 151.

placing packing strips between the tool and the tool holder, but special arrangements are sometimes used. The correct setting of the tool at centre height becomes of greater importance as the diameter of the work decreases. With tools such as the 90-degree front roughing tool, with which the chip comes away approximately parallel to the axis of rotation of the work, the tool setting is not so important and it is sometimes advisable to set the tool high because the chip is thereby made to curl outwards away from the work. The overhang of the tool beyond the tool rest should be as small as possible compatible with the tool rest clearing the lathe carrier, driving plate, etc.

Example of Lathe Work. Suppose the piece shown in full line in Fig. 152 has to be machined all over from bar stock; the operations will be as follows:

Operation	*Tool*
1. Cut off piece of bar.	Hack-saw or circular saw.
2. Centre ends.	Centre drill.
3. Rough turn one end A.	R.H. front roughing tool.
4. Turn bar end for end.	—
5. Rough turn other end B.	R.H. front roughing tool.
6. Square out corners C.	90° front roughing tool or knife tool.
7. Turn bar end for end.	—
8. Square out corners D.	As for 6.
9. Turn semi-circular groove.	Round-nosed parting tool.
10. Finish turn end A.	90° finishing tool.
11. Turn bar end for end.	—
12. Finish turn end B.	As for 10.

If an attempt is made to finish turn one end before roughing out the other, it will almost certainly be found that when the second end is finished it does not run true with the first end. When a batch of pieces is to be machined, each operation will be performed on the whole batch before proceeding to the next operation. This saves time because it is easier to take one piece of work from between centres and to replace it by another, which has a carrier fixed to it in readiness, than it is to change one tool for another; also the cross-slide graduated dial reading can be used to set the cuts and resort to measurement is largely eliminated.

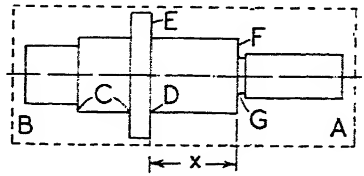

FIG. 152.

During the roughing cuts the various diameters will be measured by means of outside callipers set to a rule and the lengths between shoulders by inside callipers or by direct measurement with a rule. For the finishing cuts the diameters will be measured by means of a micrometer or a limit gauge (see Chap. 21); while using these the lathe must be stopped. The method used when the work is approaching the finished size is as follows. The work is measured and a cut sufficient to bring it to the desired size is put on by means of the cross-slide dial. The cut is started and when a length of about $\frac{1}{16}$–$\frac{1}{10}$ in. has been turned the lathe is stopped, without disturbing the tool setting or disengaging the power traverse, and the work is again measured. If any adjustment is necessary the feed is disengaged, the tool returned to the starting point, and further trials made until the correct size is attained.

The depth of the final finishing cut will depend on circumstances, but in ordinary engine lathe work it will rarely be less than 0·002–0·004 in.; in precision lathe work the final cuts may be as small as 0·0002 in. It may be remarked that the setting of a tool from a " rubbing position " is a most unreliable method and unsuitable for finishing cuts.

Usually the lengths corresponding to X in Fig. 152 are relatively unimportant and can be measured sufficiently accurately by means of internal callipers set to a rule or by a rule direct. If they are required to a higher degree of accuracy the face E should be finished first and the tool set to finish the face F by adjusting the top slide until a slip gauge can just be inserted between the face E and the cutting edge of the tool. If the perpendicularity of the faces E, F, with the axis of the work is important, those faces should be finished by setting the tool as shown in Fig. 153, and feeding it radially outwards; the accuracy will then depend on that of the lathe and not merely on the setting of the tool.

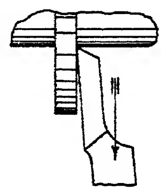
FIG. 153.

It will be seen that even the above simple job requires some four changes of tool. If the work is such that it must be held in a chuck, then all the operations must be done on each piece before removing it from the chuck (because of the difficulty of getting the work to run true once it has been removed) and all the tool changes would have to be done for each piece, thus causing much loss of time. The use of capstan and turret lathes avoids this loss as will shortly be seen.

Screw Cutting. In screw cutting the traverse of the tool has to be accurately related to the rotation of the work and also the traverse per revolution of the work is usually large compared with what it is in ordinary turning; the motion of the saddle is therefore obtained from the lead-screw. Lead-screws commonly have four threads per inch in medium-sized lathes and two threads per inch in large machines; the thread is not a square thread but has slightly sloping flanks; this is to enable the half-nuts to be disengaged from the screw by a radial motion, which is not possible with a square thread. The lead-screw has to be geared to the lathe spindle so as to give the requisite number of threads per inch on the work.

If n=number of threads per inch in lead-screw,
N=number of threads in screw being cut.

Then
$$\frac{\text{R.p.m. of spindle}}{\text{R.p.m. of lead-screw}}=\frac{N}{n}$$

and the gear train connecting the spindle and lead-screw must be arranged with that ratio. In modern production lathes the gearboxes provided enable a wide range of pitches to be obtained without having to interfere with the gearing.

The lead-screw having been geared up properly, a suitable single point screw-cutting tool is placed in the tool holder, being set correctly by means of a "screw gauge" such as is shown in Fig. 154. The saddle is then traversed to the right until the tool is about ½ in. past the beginning of the portion to be threaded and the cross-slide is fed in until a suitable cut is put on. The spindle is then started up at a slow speed and the lead-screw nut is engaged, thus causing the tool to take a cut. If the threaded portion ends in a "landing groove" (such as that at G in Fig. 152) the lathe spindle need not be stopped, but when the tool reaches the landing groove the nut must be disengaged. The tool is then withdrawn, after marking the graduated dial on the cross-slide screw so that the depth of cut can be regulated on the next cut, and the saddle is traversed back to the starting point. Devices which enable the tool to

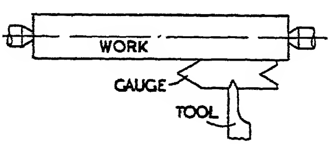

Fig. 154.

be quickly withdrawn without disturbing the setting of the cut are sometimes provided. The tool is then fed in past the previous position by a suitable amount and all is ready for the next cut. But unless the number of threads per inch in the work is an exact multiple of the number per inch in the lead-screw, precautions must be taken to engage the nut correctly with the lead-screw; unless this is done the tool will not engage in the previously cut thread and the work may be spoiled and the tool broken. To ensure proper engagement of the nut, the following procedure is followed. Before taking the first cut the saddle is traversed to the right, past the end of the work by about 1 in., and the nut is engaged. The spindle is then turned until the saddle has traversed a distance of about $\frac{1}{4}$–$\frac{1}{2}$ in. and is then stopped; a mark is made on some portion of the spindle so as to coincide with a mark on a fixed part of the headstock and similarly a mark is made on a portion of the lead-screw against a mark on a fixed portion of the lathe. A mark is also made on the bed-way to record the position of the right-hand end of the saddle. The first cut is then taken as described. When the saddle is returned after the first cut, its end is made to coincide with the mark on the bed-way and, *before engaging the nut*, the spindle is rotated until the mark on it and that on the lead-screw both coincide with their respective fixed marks; the spindle may be stopped when this coincidence is attained and the nut be engaged, but with practice the nut can be engaged just at the moment of coincidence without stopping the spindle. The second cut is then taken and the performance is repeated for subsequent cuts. Modern lathes are fitted with indicators which make the above procedure unnecessary. When the depth of the thread approaches the finished size, it is a good thing to feed the tool along by a very small amount by means of the top slide at the commencement of each cut; this causes the tool to cut on one side of the thread only and helps to produce a good finish. Threads are usually finished by means of a "chaser" since a single-point tool cannot machine the radius at the crest of the thread; but a die nut may be used instead. An example of a chaser is shown in Fig. 155; it is substituted for the single point tool and the procedure is then as described until the thread is down to size. Care must be taken to ensure correct engagement of the chaser with the threads of the work. This is done by engaging the nut and traversing the saddle along, by revolving the spindle, until the middle of the thread is reached, the chaser being then place in the tool holder, and made to engage with the threads of the work by traversing the top slide. A similar procedure is necessary if the single-point tool is removed from the tool holder during the cutting of the thread. If the thread is a short one it will generally be quicker to leave the nut engaged with the spindle and turn the lathe spindle backwards until the starting position of the saddle is reached. This is particularly so if the spindle has a reverse motion.

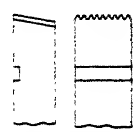

FIG. 155.

If a quick-acting reverse drive is provided to the lead-screw, it can be used for the return of the saddle but only if the clutch by which the drive is engaged or disengaged is capable of engagement in one position only.

When a landing groove cannot be provided and the thread comes to a dead end, the lathe must be stopped when the tool approaches the end of the thread and the spindle pulled round the last turn or two by hand ; this emphasises the importance of providing landing grooves.

Taper Turning. Tapered or conical parts can be machined in three different ways and the choice of method will depend chiefly on the magnitude of the included angle of the taper and on whether a lathe having a taper attachment is available. For sharp tapers (i.e. having a large included angle) and for short slow ones the simplest method is to set the top slide round to the appropriate angle on the swivel and to feed the tool, by hand, along the top slide. For slow tapers an alternative method

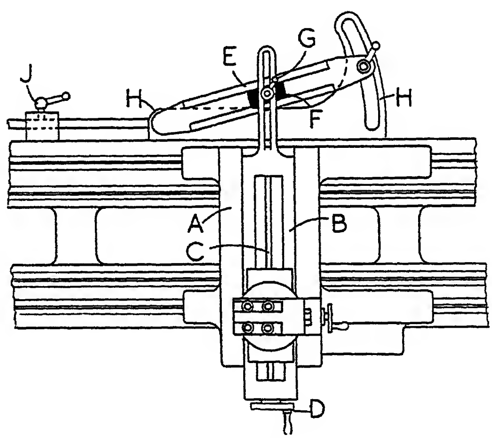

FIG. 156.

is to " set over " the tailstock by an appropriate amount ; this clearly makes the axis of rotation of the work lie at an angle to the line of travel of the saddle and thus makes the work tapered. Clearly this method is limited to quite slow tapers. The remaining method is by means of a taper turning attachment and the principle of this is shown in Fig. 156. Between the saddle A and the slide-rest assembly is an auxiliary cross-slide B which during cylindrical turning is clamped to the saddle, the tool being adjusted by sliding the slide-rest assembly on the auxiliary slide B by means of the screw C and handwheel D. For taper turning the slide B is unclamped from the saddle and is clamped at G to the

block F that slides in the adjustable slotted member E; the latter is carried on a bracket H that is supported by, but normally is free to slide along, a machined face at the back of the lathe bed. When the taper attachment is to be used the bracket H is locked to the bed by a clamp indicated at J. During taper turning with this attachment the cut can be put on by means of the wheel D and screw C in the usual way. The clamp at G must be released when the slide B is clamped to the saddle.

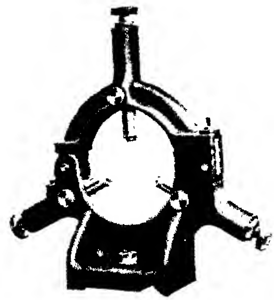

FIG. 157.

Turning Long, Slender Work. When long, slender work is being turned, provision must be made to prevent the cutting forces from bending the work. If this is not done the work cannot be turned accurately parallel. To support the work *steady rests* are used; they may be either stationary rests that are fixed to the lathe bed or travelling rests that are carried by and traverse with the saddle. Stationary rests have usually three supporting fingers as may be seen from Fig. 157; travelling rests are commonly shaped as shown in Fig. 158 and bear on the work at two points just behind the cutting tool. They are carried on the saddle. Stationary rests are frequently used to support one end of a long piece of work, the other end of which is held in a chuck; this enables drilling and boring operations to be done on the end of the work. When a stationary rest is used a small length of the job must be machined for the steady arms to bear on; this can be done quite easily if light cuts are taken.

FIG. 158.

Special Lathes. These are machines which, while being fundamentally lathes, are adapted to be particularly suitable for some operation which is of very frequent occurrence, or which calls for special arrangements. Examples of such special lathes are axle lathes, railway-wheel lathes, crankshaft lathes, gun lathes, and multi-tool lathes. The latter are perhaps worth brief consideration here, but for the others space is not available. Capstan and turret lathes also are special forms of lathe, but they are of sufficient importance to deserve a chapter to themselves. A typical multi-tool, high-production lathe is shown in Fig. 159. It differs from any ordinary engine lathe chiefly in being very massive so as to be able to take heavy cuts without vibration or distortion and in having a number of tool holders each of which can hold several tools, all of which can be in action at once. These lathes are particularly adapted to turn short shafts having several diameters, a type of job that is of

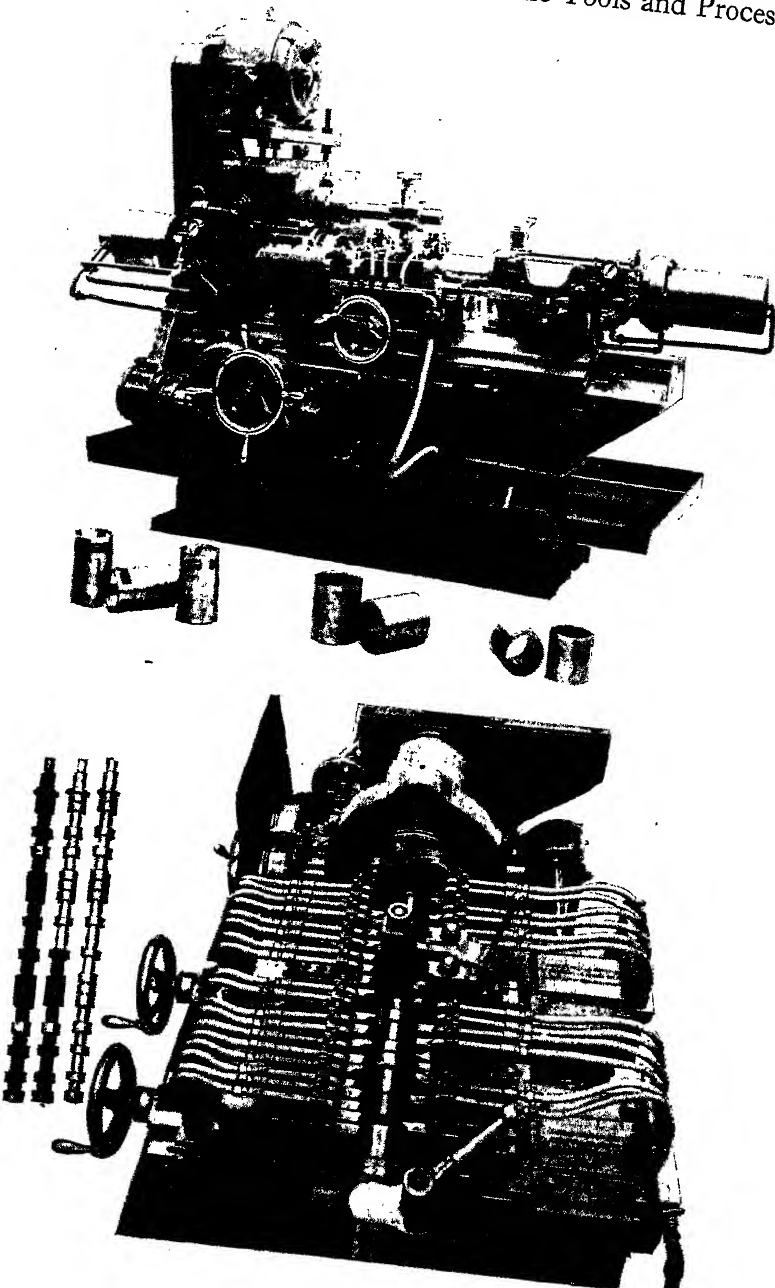

Fig. 159.

frequent occurrence, and Fig. 160 illustrates what this type of lathe can accomplish, the job shown being done in 4 mins. 40 secs.

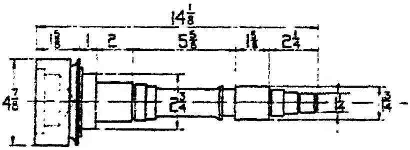

FIG. 160.

The Vertical Lathe and Boring Mill. This is, basically, a lathe turned on its end but, as will be seen from Fig. 161 which shows a vertical lathe, there are actually several important differences. The tailstock has disappeared so that all the work done by the machine is held either in a

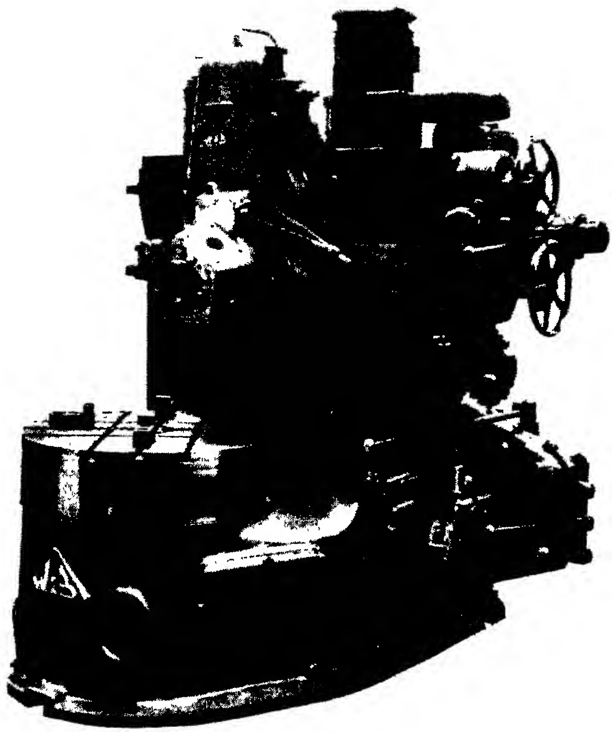

FIG. 161.

chuck or by being clamped direct to the machine table, which corresponds to the faceplate of an ordinary lathe. The saddle and slide rest of the ordinary lathe are replaced by the cross-beam and tool head of the vertical lathe and a revolving turret is provided by means of which

several tools can be mounted ready for use at any instant. The vertical feed of the tool is obtained by actuating the tool slide in the tool head saddle, the cross-beam being fixed in the machine shown. The tool slide can usually be set round at any angle so that tapers can be machined. This type of machine is made with work tables ranging in diameter from about 2 ft. up to as much as 40 ft. In the larger machines the cross-beam is usually carried on two columns and is adjustable vertically to accommodate different heights of work. One big advantage of the vertical lathe is that the centering of the work on the work table is relatively easy because the weight of the job has not to be contended with as it has to be when centering work on the faceplate of an ordinary lathe. Accessibility of the job is also somewhat better and probably accounts for the use of such lathes for small work.

Chapter 11

TOOL LIFE. EFFECT OF TOOL ANGLES, CUTTING SPEEDS AND FEEDS. POWER CONSUMED

If a tool is set to cut a bar of material under definite conditions of cutting speed, depth of cut, feed, etc., it will go on cutting satisfactorily for a time but, sooner or later, it will cease to cut properly and will have to be reground. The time required to bring about breakdown of the tool in this way is called the *life* or *durability* of the tool. The moment of failure is generally fairly well defined by changes in the appearance of the machined surface, but is sometimes indefinite. A sudden increase in the horizontal component of the force acting on the tool is said by some investigators to mark the moment of tool failure but this requires a dynamometer for its measurement. The life of a tool has been found to depend on many factors but the following are the most important ones.

1. The cutting speed.
2. The physical properties of the material being cut.
3. The area of the cut being taken.
4. The ratio of the feed to the depth of cut.
5. The shape of the tool and its angle.
6. The chemical composition of the tool and its heat treatment.
7. The nature and quantity of any cutting fluid used.
8. The rigidity of the tool, work, and machine.

Definitions. Referring to Fig. 162 the *cutting speed* is given by the expression πDN where N is the r.p.m. of the bar; the *depth of cut* is *d*, the difference between the radius of the bar before and after taking the cut; the *feed* or traverse is the distance S travelled by the tool during one revolution of the work; the *area of cut* is strictly the area shown shaded but is always taken to be equal to $d \times S$, the product of depth of cut and feed.

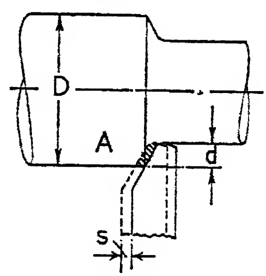

FIG. 162.

Experimental Laws relating to Cutting Tools. Experimental work on cutting tools was started towards the end of the nineteenth century and still continues. Most of it has been directed towards the determination of the effects of the factors listed above on the tool life, but despite the large amount of work done only a few of the factors have been at all widely examined, and some disagreement still persists in regard to some of the results obtained. Because of the number and complexity of the factors involved it is very difficult to keep all except

one constant and anomalous results are frequently found. A bibliography of the most important books and papers on the subject is given at the end of this chapter which is largely based on the results recorded in those papers.

Tool Life and Cutting Speed. F. W. Taylor [1] as a result of his very extensive series of experiments, formulated a law relating cutting speed and tool life ; it is :

$$VT^{\frac{1}{8}}=C$$

where V=cutting speed, usually in feet per minute ;
T=life of tool, usually in minutes ;
C=a constant whose value depends on the factors listed above.

This law enables the appropriate cutting speed to give any desired tool life to be calculated, once the value of the constant C has been determined by making a single experiment to find the tool life at one selected cutting speed.

Taylor's experiments were all made on comparatively heavy cuts and, for such cuts, have been confirmed by the Manchester experiments.[2] Other workers, however, have found different values for the index of the life T, varying from $\frac{1}{5}$ to $\frac{1}{10}$. For light cuts the law does not hold at all ; Dempster Smith and Arthur Leigh [3] found that for light cuts the tool life varied with the cutting speed as shown in Fig. 163. In some

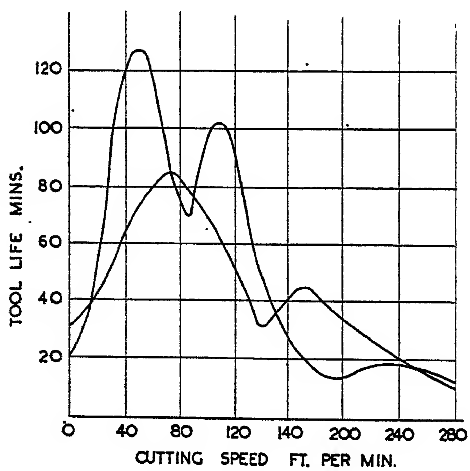

FIG. 163.

experiments the number of " humps " was two and in other experiments, with different tools, three, and the number of humps seemed to be related to the number of humps found in plotting the hardness of the

tool, as determined by the Herbert pendulum test, against the temperature, as shown in Fig. 164.

As the feed was increased, keeping the depth of cut constant, the curve

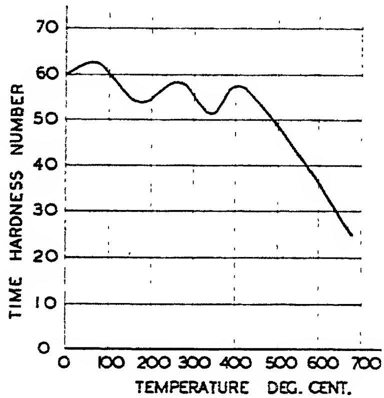

Fig. 164.

in Fig. 163 tended to move bodily to the left so that the number of humps decreased; the use of a cutting fluid, however, tended to move the curves to the right.

The Most Desirable Tool Life. What the tool life should be in order to achieve the most economical results depends principally on the time taken to remove the tool from the machine and replace it by another and on the cost of regrinding the tool. Generally speaking the simple machines such as engine lathes require a shorter tool life than the more complicated ones such as multi-spindle automatics; operations such as gun boring also require lengthy tool lives. In the "Manual on Cutting Metals" the following lives are suggested as being economically suitable:

Engine lathe	40 minutes with ordinary tool setting.
	120 minutes with accurate tool setting.
Capstan and turret lathes . . .	120 minutes.
Auto-lathe	400 minutes.

The Effect of the Physical Properties of the Material. It is well known that different materials vary greatly in their machinability and that the latter is not directly related to the tensile strength of the material. It is also fairly certain that some crystalline structures facilitate machining while others make it difficult, but sufficient knowledge is not available to enable any generalisation to be made. For a series of steels of similar composition but varying in tensile strength and Brinell hardness the Manchester experiments found the machinability to be related to those

quantities as shown by the graphs in Fig. 165, but it is now known that the machinability does not increase continuously as the Brinell hardness decreases, there being an optimum hardness below which the difficulty of machining increases. It is frequently easier to machine a material in

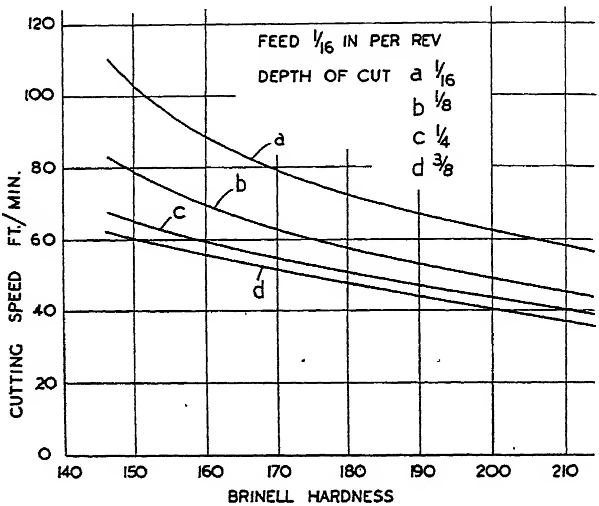

FIG. 165.

the "heat-treated" condition than in the fully annealed condition. Again, the inclusion of small percentages of certain elements, notably lead and sulphur, in steels greatly facilitates the machining although those elements, in the proportions used, have practically no effect on the tensile strength or Brinell hardness of the steel. The austenitic stainless steels, because of their work-hardening properties, are somewhat difficult to machine and it is essential to keep the cutting tools sharp; additions of sulphur, selenium, silver, and zirconium are sometimes made to these steels to improve their machinability.

Cutting Speed and Area of Cut. The early Manchester experiments, according to Nicolson and Smith,[4] established the following relationship between the cutting speed giving a certain tool life and the area of the cut:

$$V = \frac{k}{A+b} + c$$

where A is the area of cut and k, b, and c are constants. Taylor, however, stated that no simple relationship existed and this is confirmed by later experiments made at Manchester [5] which gave the results plotted in Figs. 166 and 167.

The latter graph is somewhat remarkable in that it shows a definite minimum cutting speed, for a given tool life, when the ratio of feed to

depth of cut is slightly less than unity. This result is, however, to be expected because the "crowding" of the chip in the region of the curved nose of the tool produces a higher and more localised pressure on the

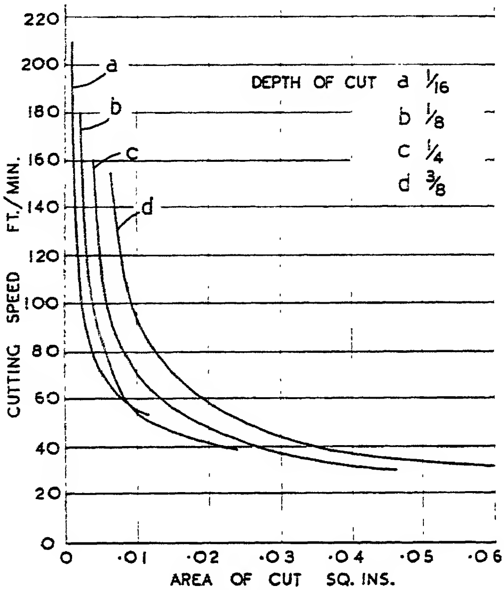

Fig. 166.

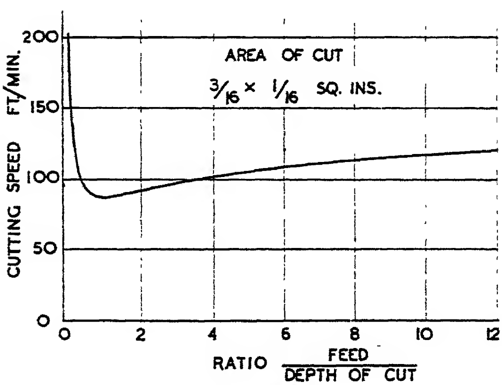

Fig. 167.

surface of the tool than when the chip is spread out along a greater length of cutting edge. Dr. Kronenberg, of the research department of the Cincinnati Milling Machine Company, however, states [6] that for practical values of the ratio, feed to depth of cut, the effect of variation of that ratio

is unimportant and he gives, and uses, the relationship $V = CA^{-n}$ ft. per min. where C is a constant whose value depends on several factors, A=(area of cut in sq. in.)×1,000, and the index n ranges from 0·28 to 0·73 according to the material being cut. Kronenberg's values for C and n are given in the table below.

Material	C: *Tool life* 60 mins. *no cutting fluid, or* 480 *mins. with cutting fluid*	C: *Tool life* 60 *mins. with cutting fluid*	C: *Tool life* 480 *mins. no cutting fluid*	*n*
Light alloy	2,160*	—	—	0·73
Brass	575	—	—	0·62
Cast brass	365	—	—	0·44
Cast steel	131	182	91	0·36
Carbon steel—				
SAE 1015	258	360	180	0·41
1025	206	288	144	0·41
1035	164	230	115	0·41
1045	131	182	91	0·41
1060	84	118	59	0·41
Cr-Ni steel	141	198	99	0·57
C.I. 100 Brinell	187	260	130	0·28
150 ,,	119	168	84	0·28
200 ,,	67	94	47	0·28

* No cutting fluid used.

The above values of C are for an 18–4–2 type of high-speed steel tool; for other types of tool the appropriate value of C may be obtained by multiplying the value given above by the factors given in the table below.

Tool composition *W*	*Cr*	*Va*	*C*	*Co*	*Mo*	*Factor*
14	4	1	0·7 –0·8	—	—	0·83
18	4	1	0·7 –0·75	—	—	0·94
18	4	2	0·8 –0·85	—	0·75	1·0
18	4	3	0·85–1·1	—	—	1·08
18	4	1	0·7 –0·75	5	0·5	1·11
18	4	2	0·8 –0·85	10	0·75	1·28
20	4	2	0·8 –0·85	18	1·0	1·33
Cemented carbide tools						up to 5

Since the weight of metal removed per minute is proportional to the product, *area of cut × cutting speed,* it follows from the preceding paragraph that there is no simple relationship between the weight of metal removed per minute and the area of cut. Fig. 168 shows some results obtained in the later Manchester experiments [5] and brings out the fact that in general a deep cut with a fine feed removes more metal per minute than a shallow cut with a coarser feed giving the same area of cut.

The Effect of Tool Angles. Variation in the true cutting angle of the tool, all other factors being constant, gave [5] the results plotted in Fig. 169. With a deep cut a well marked maximum occurs with a tool

angle of about 73 degrees but with a shallower cut, and coarser feed, the maximum is less well marked. The material being cut was a 0·39 carbon steel but steels with other carbon contents gave similar curves, the optimum cutting angle being higher the greater the carbon content.

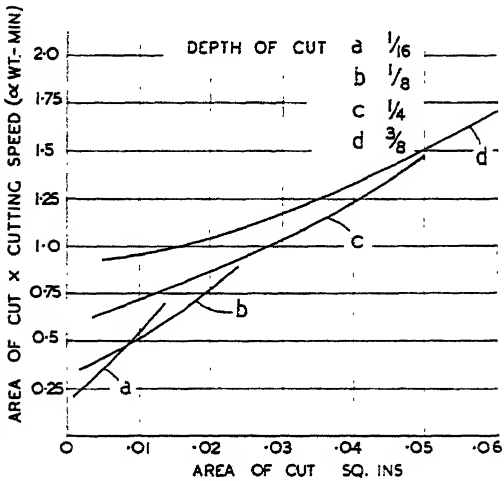

Fig. 168.

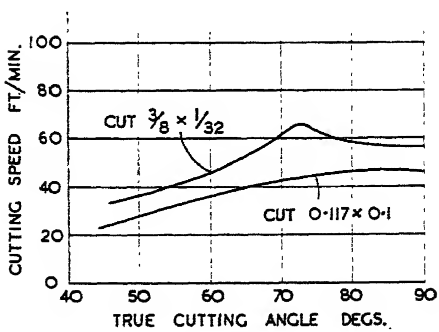

Fig. 169.

The effect of variation of plan angle is shown in Fig. 170 the 90-degree tool having the lowest specific cutting speed. Nevertheless such tools are very widely used in practice because their use eliminates the separate operation involved in "squaring out" the corner of the work when tools with other plan angles are used. Conversely the 30-degree tool is little used because it has a great tendency to "chatter" and unless the tool, work, and machine are all very rigid this chattering will prohibit the use of the tool.

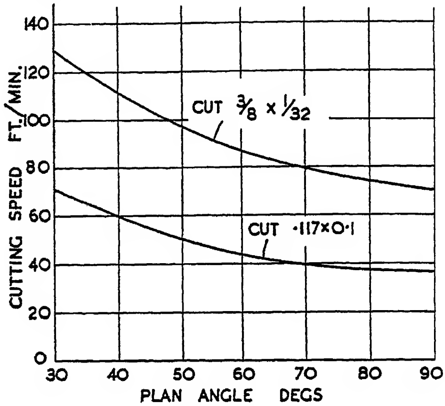

FIG. 170.

The Power Consumed. This is affected by the cutting angle of the tool as is shown by Fig. 171. It will be seen that, as would be expected, the greater the cutting angle the higher the power consumed. It will also be seen that a deep cut with a fine feed takes more power than a

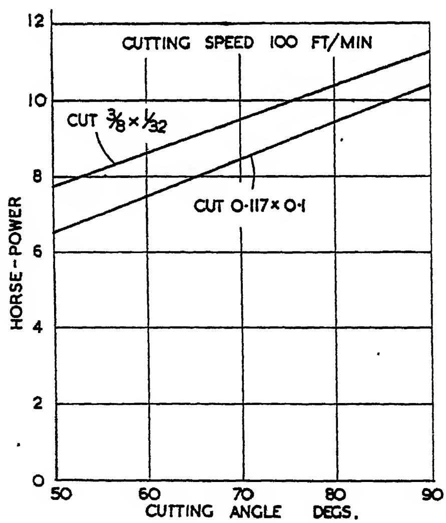

FIG. 171.

shallow cut with a coarse feed for the same area of cut. With a given tool, cut, and material being cut the power taken varies directly as the cutting speed.

It will be seen that while a great deal has been done on the problem of cutting tools only the fringe of the subject has as yet been explored,

and so the use of cutting tools in workshops remains much more of an art than a science, and this is likely to be true for many years to come. Experience and repeated trial will thus always play a large part in the determination of suitable cutting speeds, feeds, etc. The experimental results quoted above will, however, enable the effects of any alterations in the cutting conditions to be visualised and should reduce the amount of trial necessary to establish the best conditions in any given practica example. A very large amount of empirical data has been accumulated throughout the last twenty years or so and a great deal will be found collected together in the " Manual on Cutting Metals " published by the American Society of Mechanical Engineers, 1939.

Diamond Cutting Tools. Suitably lapped diamonds held in special holders are extensively used for the accurate machining of such things as light-alloy pistons and for the fine boring of holes in boring machines of the type described on p. 215. Diamond tools take only very fine finishing cuts and fine feeds are always employed. Cutting speeds are high and may range up to 2,000 ft. per min.; the feeds are of the order of 0·0005 in. per revolution. Mirror-like finishes and exceptional accuracy are possible with these tools.

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Chapter 12

CAPSTAN, TURRET, AND AUTOMATIC LATHES

Capstan and turret lathes are essentially similar in their general arrangement and operation and can be considered together. A typical capstan lathe is shown in Fig. 172 and a turret lathe in Fig. 173. They consist of a bed, an all-geared headstock, and a saddle which follow engine lathe practice; the tailstock of the engine lathe is, however, replaced by a turret, and the cross-slide is not fitted with a compound rest but merely

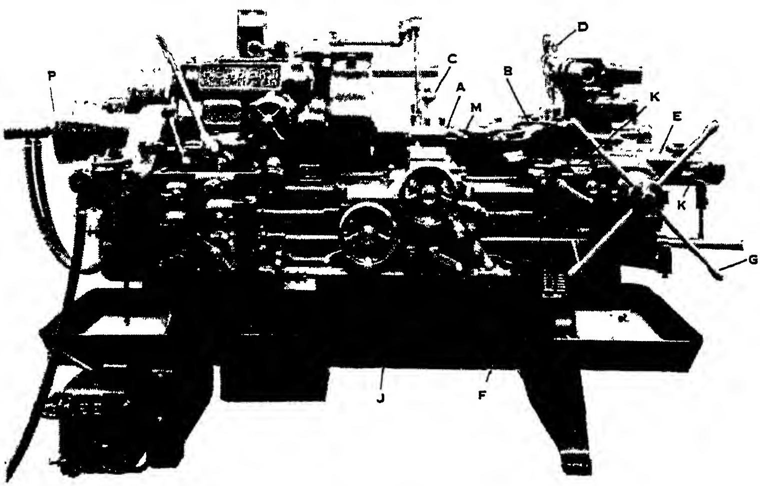


FIG. 172.

carries a revolving tool-post turret A that can hold four tools at once. Any one of these tools can be brought into the working position by unlocking the turret by means of the lever C, and turning it round manually. The main turret B carries tools of various kinds in special holders that are bolted up to its faces, it can revolve about a vertical axis, and is locked and unlocked by the lever D. In the capstan lathe the turret is carried on the slide E which slides in the sub-bed F and the latter may be clamped to the main bed in any desired position; in the turret lathe the turret is carried on a saddle which slides directly on the main bed; this is the essential difference between the two machines.

Most of the plain turning operations are done by tools held in the turret, the cross-slide being used for forming tools, tools for operating on the backs of flanges, and for parting-off tools, all of which cannot be used on the turret without making special arrangements. Parting-off tools

are generally held, in an inverted position, in a tool post provided at the rear of the cross-slide. In the capstan lathe the turret may be operated by the capstan G manually or by a power feed ; in the turret lathe the power feed is mostly used and a high speed return motion is also provided. In both machines the turrets are arranged to turn automatically, after unlocking, from one station to the next ; in the capstan lathe when the slide E is moved to the extreme right and in the turret lathe when the lever H is operated.

One of the principal points of difference between engine lathes and capstan and turret lathes is that the last two are fitted with adjustable stops to limit the motion of the saddle, cross-slide, and turret slide. Since four separate tools may be carried in the cross-slide tool post and since each of these tools will probably require the saddle to be stationed in a different longitudinal position from the others, four independent stops are provided ; these can be seen on the bar J that carries them in both Fig. 172 and Fig. 173. This bar is turned through one step each

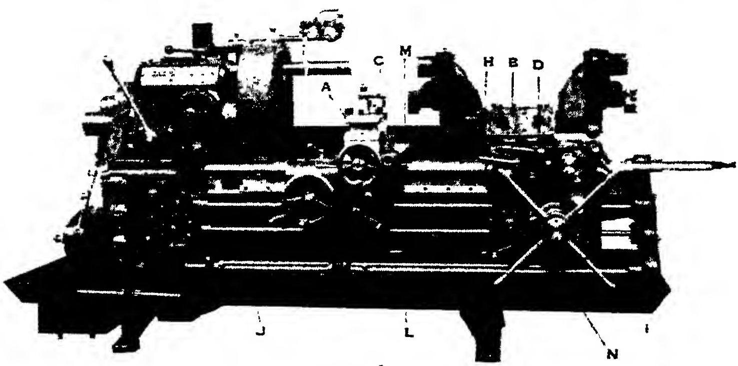


FIG. 173.

time the turret A is turned a step, the motion being produced automatically in the turret lathe and manually in the capstan lathe. The stops for the sliding motion of the capstan turret are carried on a spindle that can just be seen at KK and which is turned automatically from station to station as the turret is turned ; the stops for the sliding motion of the turret-lathe turret are carried on the bar L which also is moved synchronously with the turret. The stop bar for the cross motion of the cross-slide is situated on the saddle at M.

Capstan and turret lathes are not usually fitted with any lead-screw such as is found in engine lathes, and screw threads are usually cut by means of *die-heads* which are considered later on. Short lengths of lead-screw called "chasing screws" are sometimes provided, these being changed when different pitch threads are required.

Quick-acting chucks are generally used ; these are of the collet type

for bar work but for chuck work ordinary type chucks are used but are generally arranged to be operated by compressed air. The air cylinder for operating the chuck is seen at P in Fig. 172.

It will be understood that once the tools in the turret holders have been set to turn the proper diameters and the stops on the stop bars have been set to determine the correct lengths for the turret turning tools, and the correct longitudinal or radial positions for the cross-slide tools, then the operation of the machine is comparatively simple and merely consists in selecting and engaging the right spindle speeds and correct feed rates for each operation in sequence and then operating the appropriate levers. This can be done by semi-skilled labour and capstan and turret lathes are extensively operated by such labour after they have been "set-up" by skilled men.

Clearly the setting up of a capstan lathe will take some time; this may be as little as a quarter of an hour but may be considerably longer; with a turret lathe the setting-up times are longer still. Hence capstan and turret lathes cannot profitably be used in the manner described, that is, being set-up by skilled labour and operated by unskilled labour, unless a sufficient quantity of pieces is required to offset the setting-up times and the greater machine-hour rates. The minimum quantity is sometimes as small as a dozen but is generally two or three times that amount. Capstan and turret lathes, more particularly the latter, are sometimes operated on the lines of engine lathes, not being fully set up; thus the stops are not used and greater use is made of tools held in the cross-slide turret for plain turning than would be done in good turret lathe practice. Used in this way the turret lathe can show savings over engine lathes for batches of only half a dozen or so.

"Box Tools." Turning may be done in capstan and turret lathes in two ways: (*a*) by tools held in the cross-slide and traversed as in an engine lathe, and (*b*) by tools held in special holders fixed to the turret faces; these tools are commonly known as "box tools." Generally speaking the second method is the one most used, the cross-slide tools being kept for necking and forming operations, for facing cuts on shoulders and for parting-off, operations that cannot be done with tools held on the turret faces unless special and somewhat complicated fitments are used.

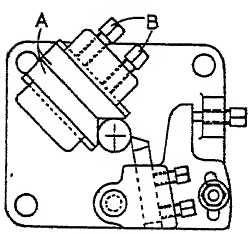


Fig. 174.

The box tools used on the turret faces are always provided with steadies to support the work under the pressure of the cut and can consequently take much heavier cuts than is possible with tools held in the cross-slide tool post when no steady can be used. This applies particularly to bar work for which box tools are mostly used. The steadies also improve the

surface finish of the work considerably because they have a burnishing action. Two examples of " box tools " are shown in Figs. 174 and 175. In the former the fingers A provide the steady and are held in a dovetail slot in the body of the holder, being locked by set screws B. The contact between the steady and the work is thus a sliding one. In the tool shown in Fig. 175 the steady takes the form of two rollers. Both holders are shown with tangential tools and both have a simple form of adjustment to enable the tool to be set to size. The steadies are generally adjusted so that they just follow the cutting tool, but when a bar has been turned with one tool and then has to be reduced in diameter for a portion of its length with another tool the steady for the latter may be adjusted to bear on the larger diameter just ahead of the cutting tool; this helps to ensure the concentricity of the two portions of the bar. Box tools adapted to carry two or three cutting tools in series, each to cut a different diameter, are commonly used when large batches of work are being put through, but for small batches separate single cutter tools would be used because they could be set up in a much shorter time.

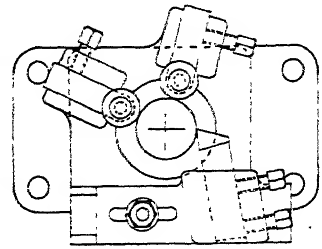


FIG. 175.

The Die-Head. The die-head is the standard tool for cutting screw-threads in capstan, turret, and auto lathes and is made in several forms, all of which, however, are similar in principle. A typical example is shown in Fig. 176. It consists essentially of a cylindrical body A, having four slots in which the chasers B are free to slide; surrounding this body is a cam-ring C whose cam surfaces bear on the outer ends of the chasers B. At their back ends the chasers have slots that engage spiral ribs machined on the end of the cam-ring member. The latter thus controls the inwards and outwards position of the chasers. On turning the cam-ring round so as to close the chasers into the cutting position a pawl engages a tooth and holds the cam-ring in position. The pawl can be

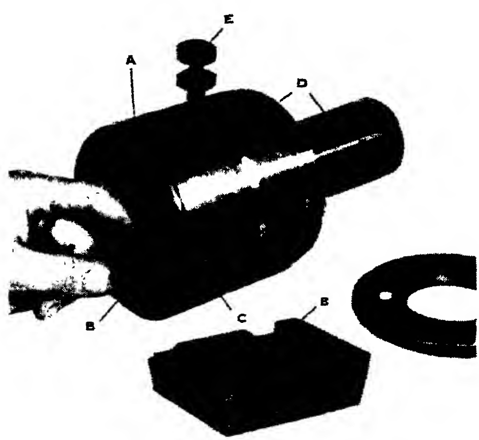


FIG. 176.

released by pulling the body of the die-head, complete with chasers and cam-ring, forwards on the shank member D. The die-head is used as follows. The chasers are closed into the working position by turning the cam-ring and the turret in which the die-head is carried is moved up so as to press the chasers against the end of the work. As the chasers cut a thread they tend to pull the die-head along over the work and the turret slide is manipulated to allow this motion to occur until the end of the thread is reached, when the turret slide is checked. The chasers and body continue to travel on, however, with the result that the pawl is disengaged from the tooth of the cam-ring and the latter, being spring loaded, turns round so as to open the chasers and free them from the work. The die-head can then be withdrawn. A fine adjustment for the size of the thread is provided at E and, in some models, provision is made for taking a roughing cut followed by a finishing cut. Clearly a set of chasers is required for each different thread to be cut.

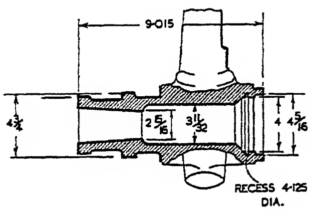


FIG. 177.

A "Tool-up" for a Turret Lathe. Fig. 177 shows the component to be machined; it is a steel forging for an aeroplane propeller hub and it is done, so far as the central boss portion is concerned, in two chuckings. The sequence of operations in the first chucking is (Fig. 178):

1. Load the forging into the special fixture mounted in place of a chuck.
2. (*a*) Face the end of the boss to length, using the tool (2) in the cross-slide turret.
   (*b*) Rough bore the taper hole to slightly less than $2\frac{15}{16}$ in. diameter, using the boring bar (2) held in the face of the turret.
3. Face the sides of the arms of the forging, using the same tool as for 2 (*a*).
4. (*a*) Rough bore the $3\frac{11}{32}$ in. and the 4 in. diameter holes.
5. Semi-finish the $3\frac{11}{32}$ and $4\frac{5}{16}$ in. holes.
6. Finish bore the $3\frac{11}{32}$, 4, and $4\frac{5}{16}$ in. holes.
7. Form the 4·125 in. diameter recess with tool number (7) held in the cross-slide.
8. Remove the forging from the fixture.

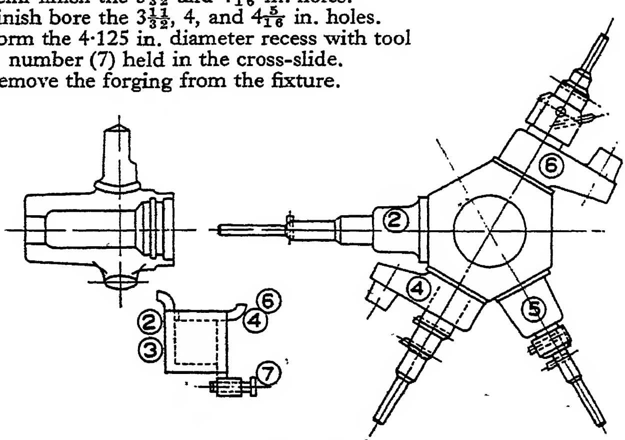


FIG. 178.

In the second chucking the forging is turned end for end and the following operations are performed (Fig. 179):

1. Load into fixture; location is on the previously machined bore and against the face machined in operation 3 above.
2. (*a*) Face the end of the boss with the tool held in the cross-slide.
   (*b*) Turn the $4\frac{3}{4}$ in. diameter boss with the " knee " tool held in the turret arm.
   (*c*) Step bore the taper hole and chamfer its end.
3. Finish turn the $4\frac{3}{4}$ and 4·385 in. diameter bosses with the tool (3) held in the cross-slide.
4. Support the forging by means of the revolving centre held in the turret, and form the grooves in the boss by means of the tools held in the back tool post of the cross-slide.
5. Rough machine the taper bore and re-chamfer it.
6. (*a*) Finish machine the taper bore by means of the reamer cutter (6).
   (*b*) Radius corner of boss with tool held in cross-slide.
7. Remove forging from fixture.

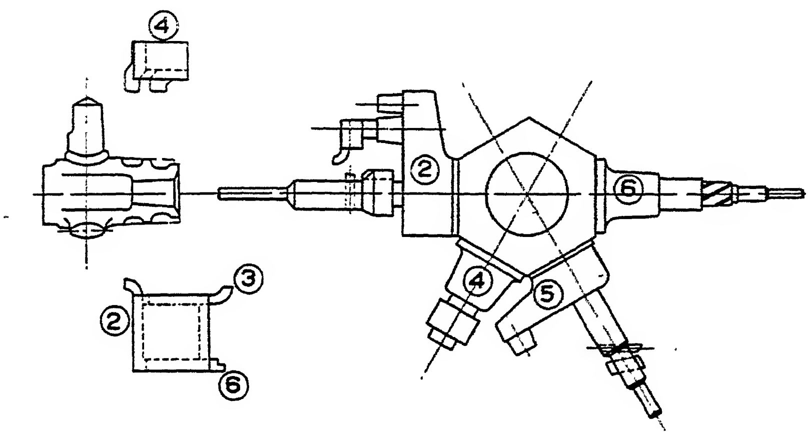


FIG. 179.

The Automatic Lathe. The automatic lathe is the logical development of the turret and capstan lathes; the general principles of all three are the same. The single-spindle automatic lathe or, shortly, the " automatic," is very similar in arrangement to a turret lathe, as will be seen from Fig. 180. The essential difference is that all the sliding movements of the turret, cross-slide, etc., which in the turret lathe are controlled directly by the operator, are controlled and produced, in the automatic lathe, by a camshaft which forms part of the mechanism of the machine. Automatics may be divided into (*a*) bar machines, and (*b*) chucking machines, the former producing articles from lengths of bar stock and the latter being used for castings and forgings. They may also be divided into (1) Single-spindle machines, and (2) Multi-spindle machines. In bar automatics the camshaft of the machine controls the opening of the chuck, the feeding forward of the bar, the closing of the chuck, and all

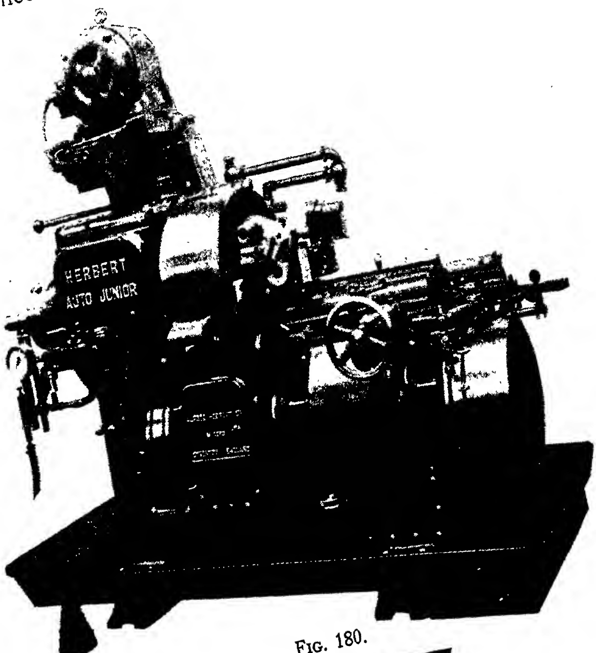


Fig. 180.

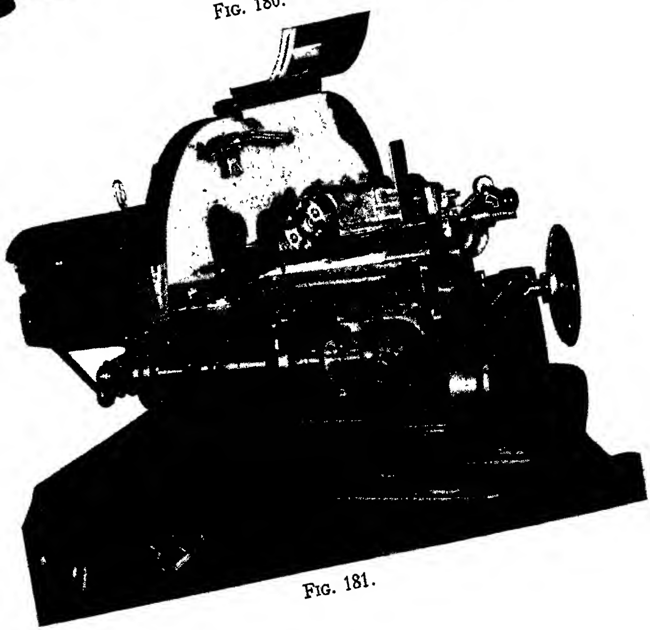


Fig. 181.

the movements of the turret and cross-slide and the operations proceed without any attention from the operator other than occasional gauging of the product to verify its accuracy and the insertion of a new bar when one has been used up. The camshaft also controls the gearbox that varies the rate of travel of the turret and the mechanism that changes the speed of rotation of the spindle. A B.S.A. bar automatic is shown in Fig. 181, where the cams controlling some of the motions will be clearly seen. In the chucking automatic the operator controls the opening of the chuck, the insertion of the work, and the closing of the chuck, but from then until the machining is finished the operations proceed just as in the bar automatic. An example of a tool-up for a chucking automatic is shown in Fig. 182*a* and *b*. The operations are as follows:

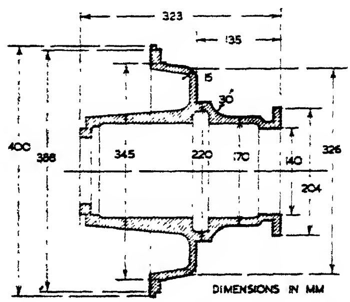


FIG. 182*a*.

1. (*a*) Turn sides of flanges with multi-tools held in special holder on front cross-slide.
   N.B.—In automatics the front and back cross-slide tool holders are independently operated.
   (*b*) Machine the 140 mm. bore and the 204 and 400 mm. diameter flanges and the 388 mm. diameter spigot. Form the 15 mm. radius corner.
2. Machine the 170 mm. diameter portion including the 30 mm. radius. This is done by a tool held in a slide that can traverse across the turret face and which is operated by the traverse of the turret in conjunction with a former held in the rear cross-slide and seen at 2 (*a*).
3. Machine the 326 mm. taper portion by means of the turret cross-sliding tool (3) and former (3 (*a*)).
4. (*a*) Size the 140 mm. bore by a floating reamer cutter.
   (*b*) Finish turn the 345 mm. spigot.

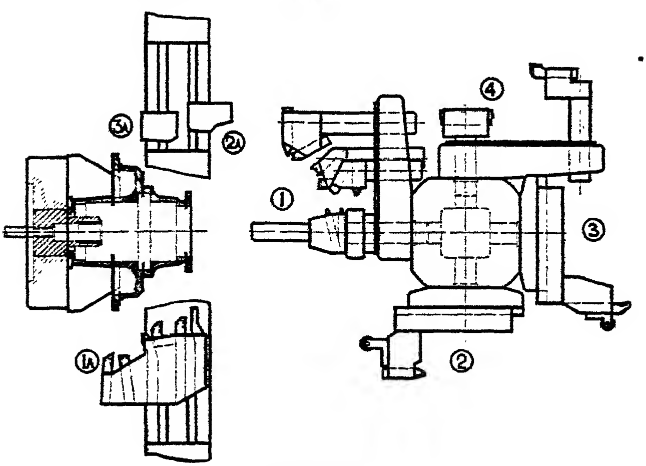


FIG. 182*b*.

Multi-Spindle Automatics. In a single-spindle automatic, while the tools used for one operation are in action, all the tools used for the other operations are idle; the multi-spindle machine is designed to enable all the tools to be kept working all the time. The underlying principle is that as many spindles are provided as there are operations to be performed, each spindle having its own individual drive. Supposing the spindles to be numbered, say, 1 to 4, and spindle number 1

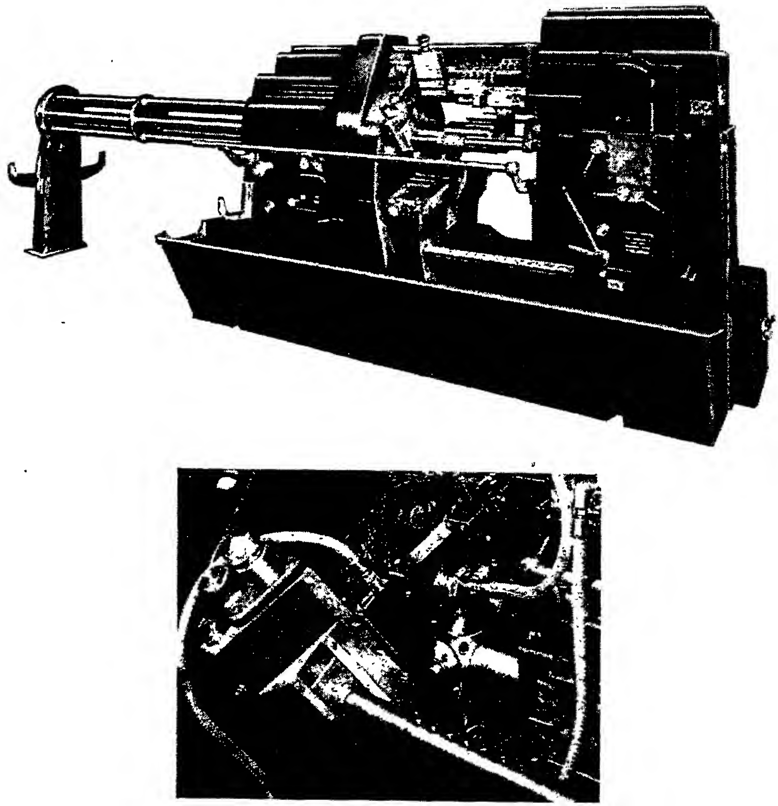


FIG. 183.

to be at the station A where the first operation is performed, then spindles 2, 3, and 4 will be at stations B, C, and D, where the 2nd, 3rd, and 4th operations are done. At the finish of these operations the head carrying the spindles is indexed round so that spindle 1 comes to station B, and spindles 2, 3, and 4 to stations C, D, and A. It will be seen, therefore, that a piece will be finished each time the spindle head is indexed and that all the tools will be working approximately all the time. A five-spindle bar automatic is shown in Fig. 183. Clearly if one operation

takes much longer than all the others it will mean that the tools for all the other operations will be idle for considerable periods, hence the operations should be planned so as to make them all occupy approximately the same time; to this end a long length of plain turning can be split up into, say, three sections, one being done at each of three separate stations.

Multi-spindle automatic lathes for both bar and chuck work are made also in a vertical form, a chucking example being shown in Fig. 184. The head in which the chuck spindles rotate can itself be rotated round the central column of the machine up and down which the tool-slides move. The chucks can thus be moved from station to station until all the operations are performed. In chucking machines one station is used for loading and unloading, this being done by the operator.

Multi-spindle automatics are built having from three up to eight spindles; they take longer to set-up than a single-spindle machine would take and consequently cannot profitably be used for such small batches of work. Similarly the single-spindle machine requires larger batches than the turret lathe.

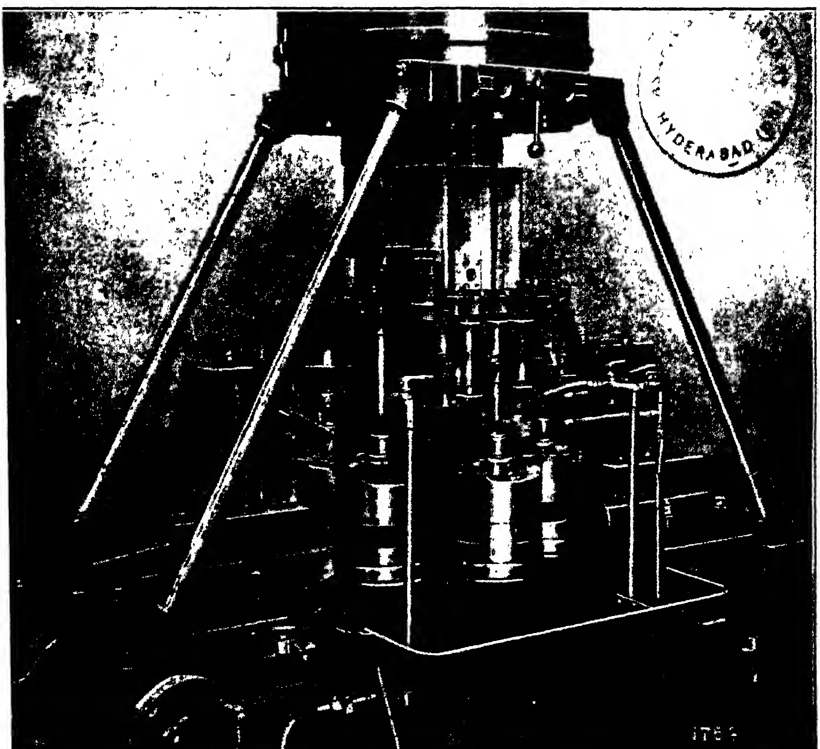


FIG. 184.

Chapter 13

THE MACHINING OF HOLES

The consideration of the machining of holes may be divided into two sections according as to whether the hole has to be produced in solid metal or whether it already exists, because of coring in castings or punching in forgings, and merely has to be brought accurately to size. To form a hole in solid metal some kind of drill must be used and so types of drill will first be considered.

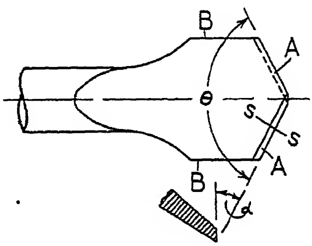


FIG. 185.

Types of Drill. The oldest type of drill is the *flat* or *spade* drill, an example of which is shown in Fig. 185. It is easily made by forging down a rod so that its end is suitably flattened and then grinding the cutting edges A and shoulders B. The angle θ is usually made about 120 degrees but is sometimes only 90 degrees. The cutting edges must be properly *backed-off* or *relieved* as shown by the section on SS, the angle α being usually about 15 degrees. In jobbing shops drills of this kind are commonly made up as required but in quantity production they are little used. A rather more elaborate type of flat drill is, however, much used for the drilling of deep holes where the depth exceeds five or six diameters. Such a drill is shown in Fig. 186 and consists of a separate blade A which is fixed in the end of a tubular shank B. A pipe C brings a supply of cutting fluid to the cutting edges and the chips produced are washed away down the hollow shank. The grooves D serve to break up the chip into a number of small pieces that are more easily disposed of than a long continuous chip would be.

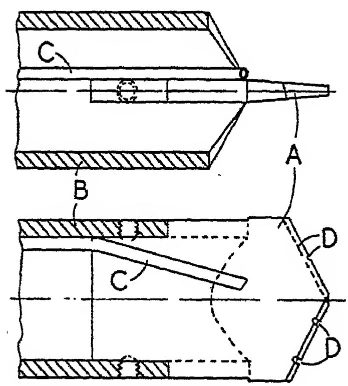


FIG. 186.

D-Bits. A simple D-bit is shown in Fig. 187. It consists of a rod whose end has been jumped up so that it is larger than the remainder and which, after the enlarged end has been machined truly cylindrical, has been cut away down to the centre line as indicated by the line OP in the elevation. The end of the bit is ground at some angle θ, less than

90 degrees, to the axis XX so that the edge RS forms a cutting edge. Relief is obtained by grinding the face T at an angle as shown. In using a D-bit the hole must first be started by means of a flat drill or a twist drill for a distance about equal to the dimension *a* and must then be bored accurately to the diameter D by means of a boring tool held in the slide rest. This gives the bit an accurate start and it will then go on, the cutting edge being guided by the cylindrical surface, and will produce a hole which will be more accurate, both as regards size and straightness, and which will have a better finish, than a twist drill or flat drill can produce. The simple bit shown must be withdrawn from the hole at intervals to allow of removal of the chips ; but by making the shank a tube, on the lines of Fig. 186, chip disposal can be arranged and continuous operation ensured. A more elaborate bit is shown in Fig. 188 ;

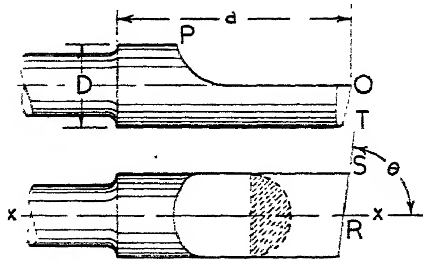


FIG. 187.

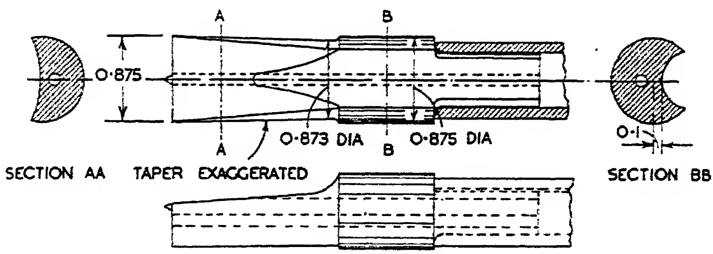


FIG. 188.

it is for rifle barrel drilling. The shank is formed of a tube swaged down to a D section and is brazed to the bit itself. The shank serves to convey the cutting fluid to the cutting edges and the chips are disposed of by passing between the flat of the shank and the wall of the hole. Fig. 189 shows, to a smaller scale, the way in which the drilling is done.

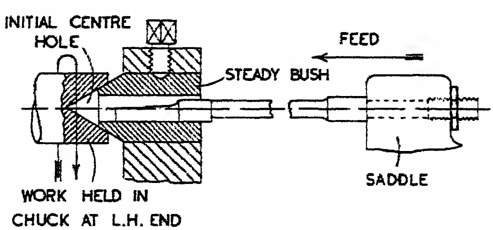


FIG. 189.

The cutting fluid is supplied under a pressure of 800–1,000 lb. per sq. in.; lower pressures have been found insufficient to wash the chips back out of the hole. In drilling rifle barrels made from 0·5–0·6 per cent carbon steel, the cutting speed ranges from 100 to 200 ft. per minute with a feed of about $\frac{3}{8}-\frac{3}{4}$ in. per minute. The feed rate is fairly critical. The cutting speed is determined largely by the nature of the macrostructure of the material, steels showing an irregular structure, or a very fine one, being much less machinable than steels having a regular, moderately coarse macrostructure.[1] The influence of the macrostructure has been found to apply to other types of cutting as well as to drilling.

Twist Drills. These are by far the most widely used type and description is almost superfluous; however, Fig. 190 shows some examples. The cutting edges are usually inclined to the axis at 59 degrees but for special purposes, such as drilling light alloys and plastics, smaller angles may be used. Usually two flutes are used and their helix angle is about 25 degrees, but again for special purposes, drills with three, four, or five flutes may be used and the helix angle may be smaller or larger than the standard value. The *lands* of twist drills are generally relieved as in the examples *a–f* and sometimes a hole is formed in the body of the drill, as in the example *c*, to carry cutting fluid to the cutting edges. The drill shown at *d* is a " core drill " for drilling cored holes. For this work drills with only two flutes are not suitable as they will not produce round holes. It is important that twist drills should be properly ground; the cutting edges should be equal in length and equally inclined to the drill axis, otherwise the drill will not drill true to size. Also the clearance or relief of the cutting edges should all be the same. These results can only be obtained easily and consistently by grinding the drills on a properly designed drill grinder.

Drilling Machines. There are numerous variations in the types of drilling machine in use but, broadly, they may all be grouped into four classes, namely: (1) Sensitive; (2) Pillar; (3) Radial; and (4) Multiple-spindle machines. The first and second groups are similar in general design but differ in size, the sensitive drilling machines taking drills up to about $\frac{1}{8}$ or $\frac{3}{16}$ in. diameter and the pillar drill up to as much as 2 in. diameter, according to its size. Sensitive machines are provided only with hand feed but the pillar type machine is frequently provided with a mechanical feed. Fig. 191 shows a typical single-spindle pillar type drilling machine; the spindle speeds can be varied from about 100 r.p.m. up to 1,100 r.p.m. and a number of different mechanical feeds is provided. In general purpose machines the range of speeds and feeds provided is usually wider, and the changes are more readily effected, than in manufacturing machines. The mechanical feed is arranged to be

[1] See " Machinability as Indicated by Macrostructure." F. E. Robinson and C. T. Nesbit, *Proc. I. Mech. E.*, March, 1932.

engaged automatically as soon as an axial pressure is applied to the spindles by means of the hand-feed levers and the feed is also automatically disengaged when the drill has been fed to any desired depth.

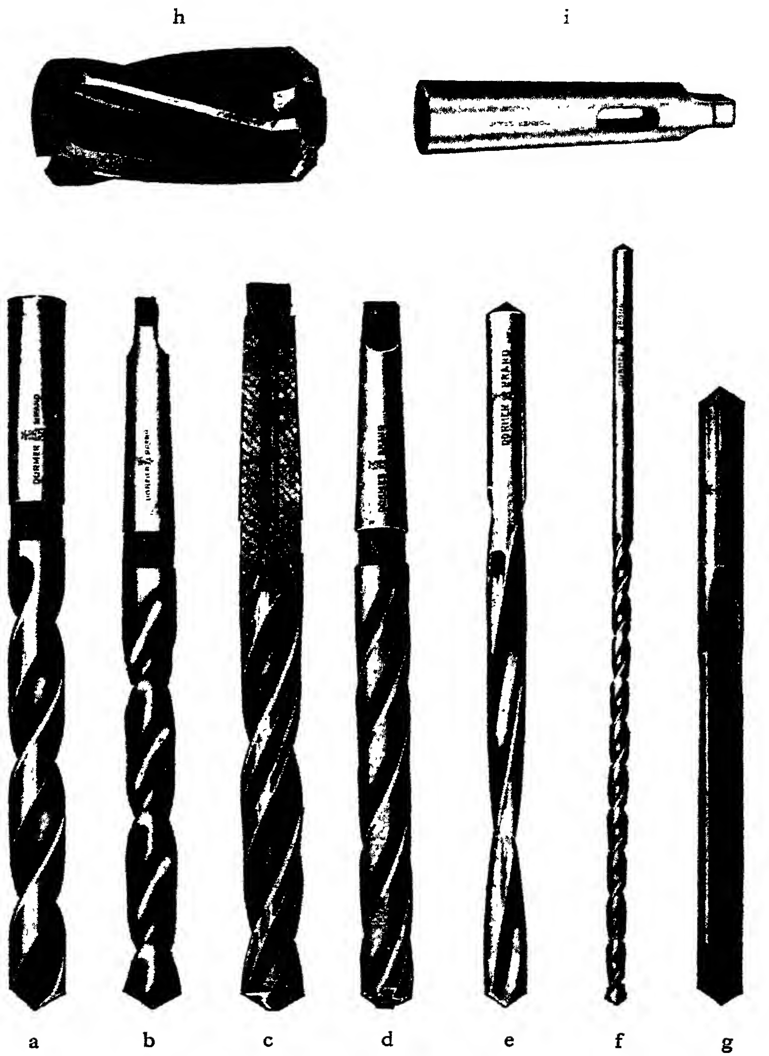


Fig. 190.

On disengagement of the feed the spindle is returned to the uppermost position by means of a counterweight or a spring. The spindle heads may be adjusted up and down the column to accommodate different

lengths of drill and the work table is also adjustable for height to allow for varying size of work. Drills larger than $\frac{3}{8}$ in. diameter are generally made with Morse taper shanks and fit, by means of adapters in the smaller sizes, the corresponding taper hole in the machine spindle. Drills smaller than about $\frac{3}{8}$ in. diameter usually have parallel shanks and

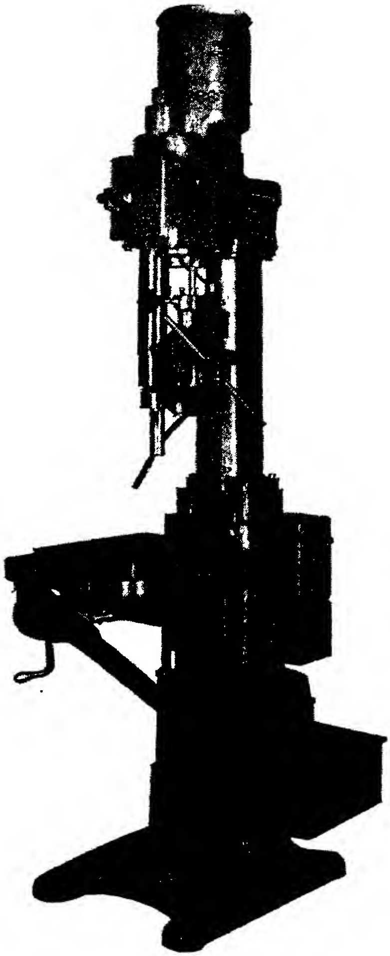


FIG. 191.

are carried in chucks which may have taper shanks to fit the spindle hole or may be fitted direct to the nose of the spindle. Machines such as this are built with up to four spindles. Clearly the work vice or jig must be moved about on the work table so as to bring the axes of the holes to be drilled underneath the drill in turn. The larger sizes of pillar drill

sometimes have work tables which can be adjusted in two directions at right angles, as well as vertically. When the work is large and bulky it is not always convenient to move it about for the purpose of centering the drill and for such work the radial drill is used. An example is shown in Fig. 192; the spindle is carried in a saddle that can be moved along

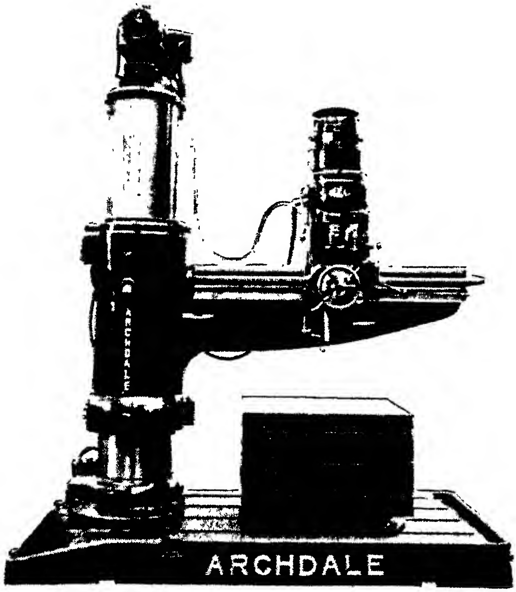


Fig. 192.

the arm of the machine while that arm itself can be revolved, together with the column, up and down which it can be moved, about a vertical axis. Thus the drill can be brought to any desired position within the range of the machine. The saddle houses all the gearing necessary to give the various spindle speeds and feeds and also carries the driving motor. All the controls are grouped so as to be within easy reach of the operator. The spindle of the machine shown cannot be inclined at any angle other than 90 degress to the surface of the bed and so, if holes are required at different angles, the work must be tilted; this can be done by means of a tilting work table but, again, for heavy work this method is not suitable and so universal radial drilling machines are made in which the spindle axis can be inclined at any angle, either by making the saddle capable of swivelling relative to the arm or by making the arm capable of rotating about its longitudinal axis relative to the column.

If a reverse drive is provided to the spindle, tapping operations can be easily performed, the taps being held in spring-loaded drivers which slip when the tap reaches the bottom of the hole.

When a large number of holes have to be drilled in a job of which a large quantity is required, the holes will be drilled all together in a multiple spindle drill, a comparatively simple example of which is shown in Fig. 193. The various spindles, of which there may be a hundred or more, are driven through universally jointed shafts and can be adjusted to any desired position, within limits; they can, sometimes, be driven at different speeds but, since they are all carried by a single head which is fed downwards, they must all receive the same feed motion and the drills

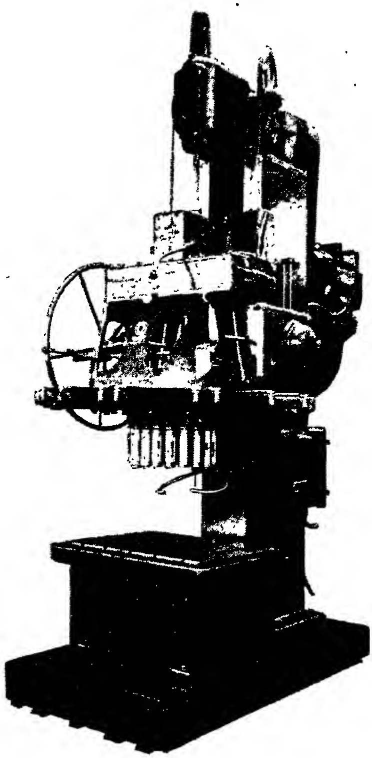
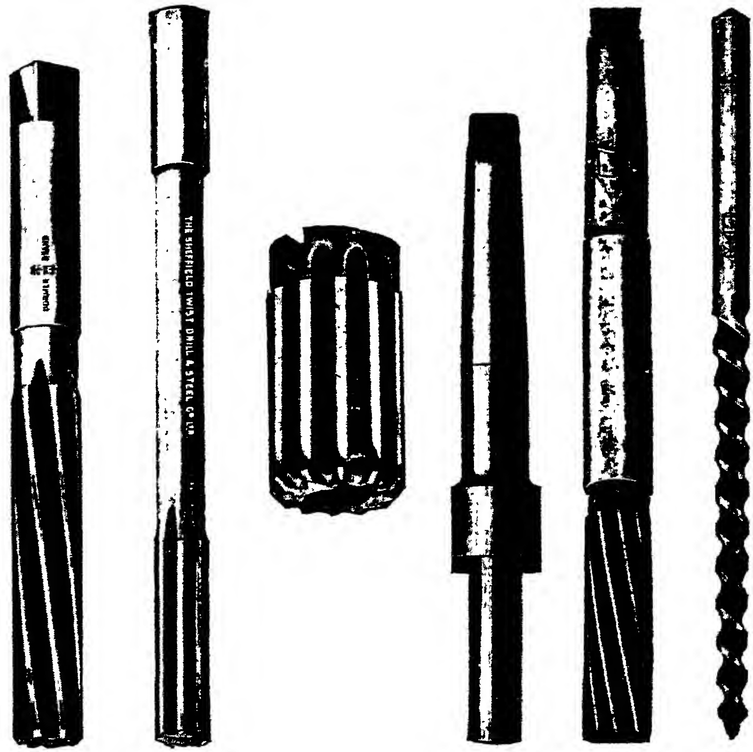


FIG. 193.

must be individually adjusted for depth of feed. A jig (see p. 218) is invariably used. More elaborate machines may have three or more heads, each having numerous spindles; thus drilling may be performed on the top and end faces of a motor engine cylinder block simultaneously. In another form of multiple spindle drill each spindle has its own driving motor and feed gear, the machine consisting of a number of similar self-contained spindle heads placed just where required by the job and carried by the frame of the machine; such machines must obviously be designed specially for the job and are single-purpose machines.

Reamers. For many purposes the holes produced by twist drills are not accurate enough in size nor do they have a good enough finish and, when this is so, the holes are frequently drilled undersize and are then finished by *reaming*. Reamers are made in various forms and a selection is shown in Fig. 194. That at *a* is a hand reamer and is slightly tapered



a b c d e f

Fig. 194.

for about $\frac{1}{2}$ in. from the end to enable it to be inserted in the hole, through which it is worked with a twisting motion, combined with an axial pressure, applied through a double-ended wrench. Fig. 195 shows an enlarged view of a reamer tooth and it will be seen that the cutting edge is provided with a definite clearance, the angle θ varying from 4 to 8 degrees. The face A of the tooth may be radial but is sometimes given a definite negative rake. The tooth is sharpened by grinding the land B whose width, in a new reamer, varies from as little as 0·01 up to 0·05 in.

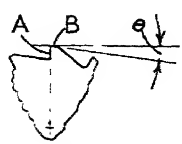


Fig. 195.

The teeth of reamers are commonly spaced at unequal intervals, but generally each tooth has another diametrically opposite to it. Some skill is required to get good results from reamers as it is fairly easy to produce bell-mouthed and tapered holes. A reamer will produce only one size of hole in a given material although the size produced by a given reamer in cast iron might be slightly different from that which it would produce in, say, aluminium alloy. For reaming blind holes " bottoming reamers " which do not have any taper at the end, except a slight bevel, are used.

Reamers for use in machines usually have fairly long bodies and taper or cylindrical shanks (Fig. 194*b*) while the toothed portion may be comparatively short. They do not usually have any tapered portion except a slight bevel, but often have the teeth formed on the end as well as along the body. Shell reamers such as that shown at *c* (Fig. 194) are also used in machines being carried on arbors as shown at *d*. Rose reamers are similar to shell reamers but their teeth are not relieved along their length but only on their ends, which are intended to do all the cutting. A jig-reamer is seen at *e* ; this has a cylindrical portion whose diameter is equal to the nominal size of the reamer and this fits in the bushes of the jig in which the reamer is used (see p. 218). " Bridge " reamers are characterised by a long tapered portion at the end and are used on structural work. The dimensions of reamers are laid down in B.S. No. 122—1938.

The number of reamers that must be carried in the tool store can be considerably reduced by the use of adjustable reamers ; these have the cutting edges formed by a number of separate blades carried in slots in the body of the reamer and various means are employed to move the blades in or out radially and to lock them in position. In badly designed, and made, adjustable reamers only a few of the blades will usually cut properly.

Hand reamers are intended only to clean up a drilled hole, removing in the process some 0·002–0·005 in. of metal ; it is consequently necessary to have a set of drills smaller than the nominal size by about that amount ; such drills are known as *reamer* drills, whereas ordinary drills whose actual diameter is equal to their nominal size are known as *size* drills.

Trepanning. This is a process which is used chiefly for initiating holes in billets as a preliminary to forging and in the manufacture of long hollow shafts. It is done in lathes by means of trepanning bars, an example of which is shown in Fig. 196. The bar is carried in the saddle of the lathe and is supported close to the end of the work by a steady ; the work is held in a chuck at one end and in a steady at the other end. The trepanning bar is fed axially and the work is rotated. Six or more tools are carried in dovetail slots in the end of the bar, one being shown at A, and grooves B are provided to enable the chips produced to get away. Each tool takes a narrow cut, as indicated on the right of the

figure, and in the result a narrow annulus of metal is cut away and a solid core thereby removed, leaving the desired hole. As the bar is fed farther

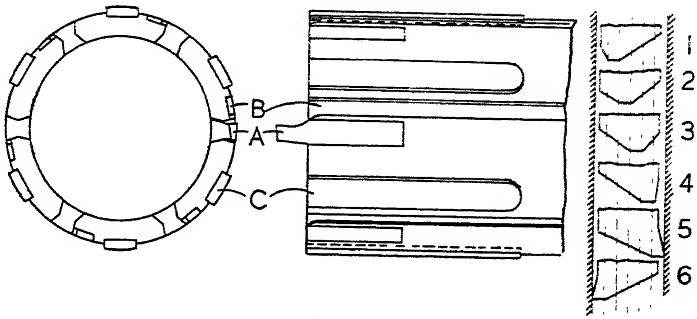


Fig. 196.

and farther into the work the overhanging weight is more and more supported on the rubbing pads C. Similar pads, inside the bar, are used to support the core. These rubbing pads are made of lignum vitæ, except those at the bottom, which are of hard brass.

Small trepanning bars, made from the solid, are sometimes used in drilling machines.

Counterbores and Spot-facing Cutters. Holes such as that shown in Fig. 197 have frequently to be machined and the usual method is by means of *counterbores*. The smaller diameter is drilled first and serves as a pilot hole for the counterbore which is of the form shown in Fig. 198. When the depth of the counterbore is negligible and the counterboring tool is used merely to clean up the metal round the hole so as to form a seating for a nut, the operation is called *spot-facing*, and may then be done by a simpler kind of cutter such as that shown in Fig. 199 where the blade is separate from, and is inserted into a slot in, the shank, which itself acts as a pilot. Such spot-facing cutters are also commonly used, in an inverted position, to spot-face the undersides of bosses.

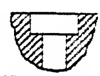


Fig. 197.

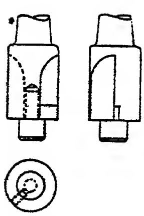


Fig. 198.

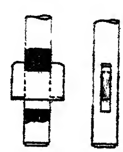


Fig. 199.

Boring Operations and Machines. Boring operations can be performed in a lathe or in a boring machine, the principles and tools being the same in both cases; the boring machine is, however, specially adapted to this kind of operation and so boring operations in the lathe will not be specifically mentioned in this article. Before dealing with the operations it will be best to describe a typical boring machine and a general

purpose machine is shown in Fig. 200. It consists of a bed which is bolted down on to a suitable foundation and whose upper surface is machined to take the work table. The latter usually is in two parts, the table proper being carried on transverse ways on the lower portion; this provides an adjustment at right angles to the bed ways. At one end of

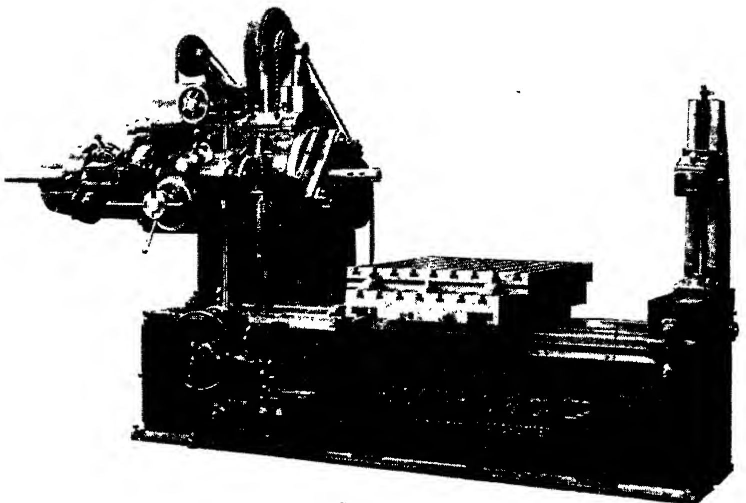


Fig. 200.

the bed is situated a column whose face is machined to take the spindle head which is consequently adjustable vertically; its weight is counterbalanced and it is provided with bearings for the spindle. This can be rotated at a variety of speeds and can also be fed axially at various rates. At the opposite end of the bed is a smaller column which carries a bearing to support the outer end of a boring bar, the other end of which is carried by the spindle.

The boring operations performed in such a machine may be divided into two groups, those done with overhanging bars or tools and those done with boring bars supported at both ends. The latter will first be considered. Referring to Fig. 201 suppose the hole shown in the work A is to be enlarged by boring; the axis of the hole will be defined by circles scribed on the ends of the work and the first operation is to set up the work so that this axis coincides with the axis of the machine spindle. It will be assumed that the bottom of the work has been machined in a previous operation and that the axis of the hole is parallel to that surface.

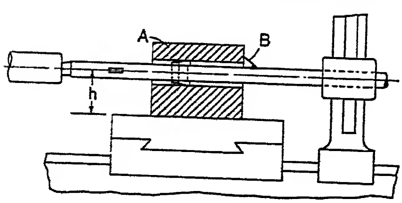


Fig. 201.

The work is placed on the machine table and clamped lightly and the spindle head is adjusted until it is approximately at the right height. A boring bar is then passed through the work and is inserted into the spindle. By means of a piece of plasticene a pin or needle is attached to the bar and its end is made to coincide with one point of the scribed circle on the end of the work. Rotation of the bar then shows whether that circle is concentric with the axis of the spindle and if it is not the spindle head is adjusted vertically and the work table horizontally until concentricity is obtained at both ends of the work. The pin and plasticene are commonly referred to as the " sticky pin." To get the dimension *h* accurate an end gauge may be used between the surface of the work table and the underneath of the boring-bar, the size of gauge being selected in conjunction with the diameter of the bar. Similar means can sometimes be used for the cross-setting of the work if a suitable side face is available on the work. Having got the work set properly it is firmly clamped down and the cross-adjustment of the work table is locked, if a locking device is provided. The spindle head is also locked to the column. A cutter is inserted into the boring bar which is rotated at a suitable speed. The spindle may then be fed axially until the cutter has passed right through the work or, alternatively, the feed may be obtained by traversing the work table. The result will be a hole whose diameter will depend on the setting of the cutter in the bar.

Boring-Bar Cutters. These are of two main types, *single-ended* and *doubled-ended*; they are made from round or rectangular section tool steel and fit into correspondingly shaped holes in the boring bar, being secured by set-screws or by more elaborate means. The double-ended

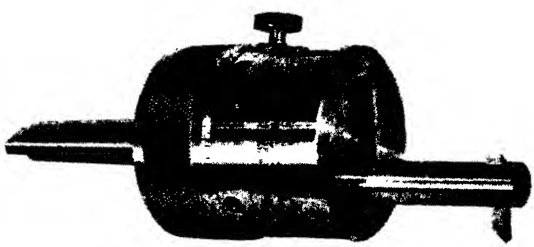


FIG. 202.

cutters must, of course, be made to the size of the hole to be bored and are usually ground to that size while in place in the boring bar, the grinding being done in a cutter grinder so that the proper amount of relief can be given to the cutting edges. The single-ended cutters can be adjusted by tapping them in or out with a hammer, a crude but effective method; elaborate boring bars with cutters that can be adjusted by means of

wedges, and similar mechanism, while the bar is rotated are sometimes used. A boring bar with several cutters mounted on it is commonly used to machine a number of holes, say the main bearing housings of a motor engine crankcase, simultaneously.

For blind holes, and for shallow holes, overhanging tools held in a kind of chuck are used ; an example of a tool mounted in such a tool head is shown in Fig. 202. The tool can be adjusted inwards and outwards radially by means of a screw and nut and a setting dial, graduated in 0·001 in., is provided. The head fits into the end of the machine spindle just as a boring bar does.

The Use of Jigs and Fixtures. When a number of holes have to be bored in a job the spacing of them at the correct centre distances can be done by using end gauges in the manner indicated above, but much time can be saved by the use of jigs, and these, and fixtures which facilitate the holding of the work, are considered in the next chapter.

Other Types of Boring Machine. The machine shown in Fig. 200 is provided with a facing head, which is driven independently of the spindle, and which can be used for facing the end of the work at the same time as the boring bar bores the hole. When this is done the boring feed must, of course, be obtained by the axial motion of the spindle. The facing tools are held in tool holders which are adjustable radially across the facing head by means of a screw and nut ; this motion can be given while the facing head is rotating. The axial motion of the spindle being controlled by a lead-screw, screw threads can be cut when required.

In the larger sizes of machine of this type it is not convenient to carry the work on a table that slides and traverses and so a fixed work table is employed. The column that carries the spindle head is then arranged to traverse on ways formed on the main bed or on a subsidiary bed ; the alignment of the spindle and hole axis is then obtained by moving the spindle head up or down the column and the column to or fro on its bed ways. The boring feed is obtained by giving the spindle an axial motion or by employing a boring bar fitted with a travelling tool-head.

For certain rather specialised work, such as the boring of motor-car cylinders and particularly for blind bores, vertical boring machines are employed, an example having six spindles being shown in Fig. 203. The centre distance between the spindles can, sometimes, be adjusted, within narrow limits, but all the axes must lie in the same vertical plane ; such machines are really single-purpose machines and they have been highly developed so as to be able to produce bores with an excellent finish and accurate to 0·0002 in. for roundness and parallelism. This result has been obtained largely by careful design of spindle bearings, the lubricating

oil for which is sometimes maintained at a constant temperature by means of thermostatically controlled heaters, by the use of rigid constructions and by using relatively high cutting speeds (of the order of 350 ft. per minute) with cemented-carbide tipped cutters. The exceptionally accurate " jig-boring machines " also all have vertical spindles.

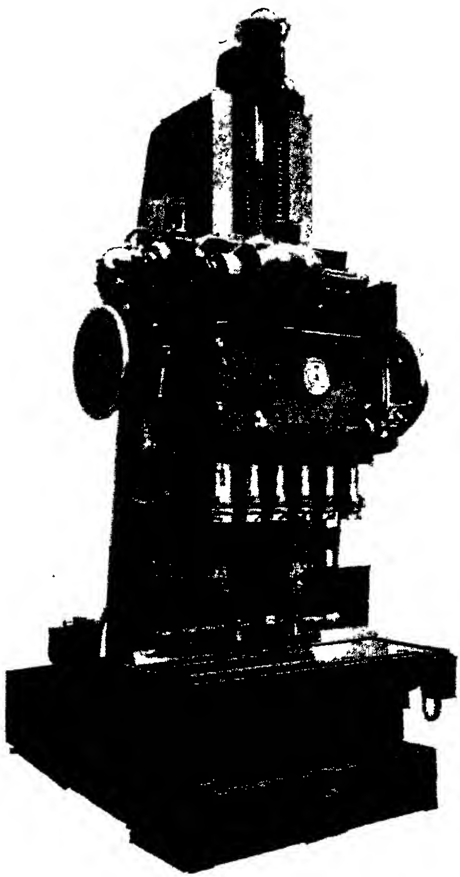


FIG. 203.

Another type of boring machine has been developed by the Heald Company and is now extensively used ; an example is shown in Fig. 204. It is essentially a production machine for the machining of parts in moderate and large quantities. As will be seen the machine consists of a massive bed on which is the work table which is provided with a longitudinal motion only. The work is carried in specially designed fixtures on the work table, quick-clamping arrangements being used as seen in

Fig. 205, which shows a 4-station rotatable fixture on a 4-spindle machine. The spindle heads are self-contained units and may be

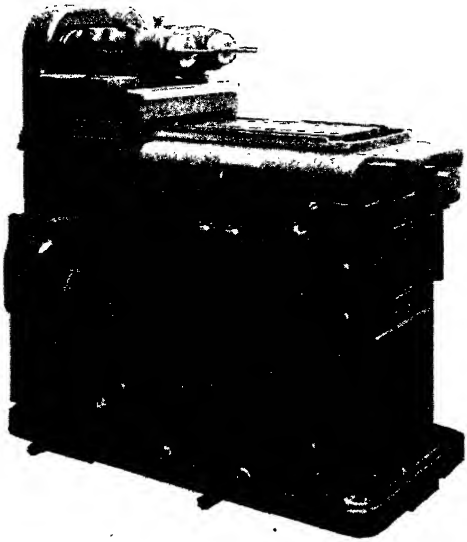


Fig. 204.

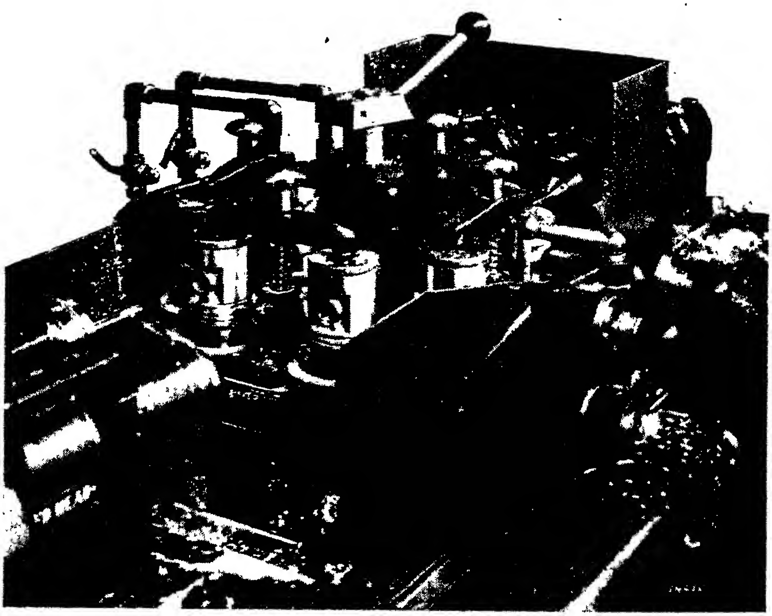


Fig. 205.

adjusted on the ends of the bed so that their axes may be made to coincide with those of the holes to be bored. Overhanging boring bars are used with single-point tools and when once set to cut to size no adjustment is made to the tool setting until tool wear brings the holes below the limit permitted on the work. Machines of this type are made single-ended, as shown, and double-ended; they may have from one to four spindle heads. The double-ended machines commonly take two or four pieces of work, those at one side of the work-holding fixture being unloaded and fresh pieces being loaded while those at the other side are being bored. For some work, such as small bushes, it is more convenient to carry the work in chucks on the spindles and to mount the non-rotating tools on the central saddle; this enables taper boring to be done since the spindle axes can be set round at an angle to the traverse of the saddle.

Accuracy Attainable in the Machining of Holes. The table below indicates the greatest accuracy ordinarily attainable at the present day in the machining of holes whose depth does not exceed about ten diameters.

Method	*Roundness Inches*	*Straightness Inches per foot*	*Size Inches*
Drilling	0·005	0·008	0·005
Reaming	0·0005	0·004	0·001
Broaching	0·0003	0·004	0·0005
Fine boring	0·0002	0·0002	0·0002
Grinding	0·0002	0·0002	0·0002
Honing	0·0002	0·0002	0·0002

Chapter 14

JIGS AND FIXTURES. JIG-BORING MACHINES. MARKING OUT

The nature of a jig can best be explained by giving an example. Suppose a number of flanges like that shown in Fig. 206 have to be drilled as shown, and it is necessary that they shall all be interchangeable.

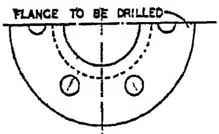
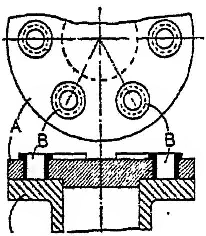


FIG. 206.

Then the drilling would be done by means of a jig such as is shown at A in Fig. 207. It consists of a circular plate provided with a spigot to fit the pipe, or a recess to fit the edge of the flange, and with hardened steel bushes B in which the drill to be used is a close running fit. The jig is placed on the flange and is clamped to it by means of some form of clamp, the drilling being then done through the bushes. The accuracy of spacing of the holes then depends almost entirely on that of the jig and scarcely at all on the skill of the operator.



Flange to be drilled

FIG. 207.

The choice as to whether the jig in the above example should be positioned by means of a spigot entering the pipe or by having a recess to fit the edge of the flange will depend on circumstances, such as which surface is machined and with which it is the more important that the holes should be positioned accurately.

If the holes had to be reamed after drilling, two sets of bushes would be used, one for the drills and one for the reamers; the bushes would then be made a push fit in the body of the jig and would be prevented from turning by a peg fitting a recess in the flange of the bush. If the jig was to be used for a long period then the holes in the jig body would be lined with hardened liners to avoid wear due to the constant insertion and removal of the guide bushes.

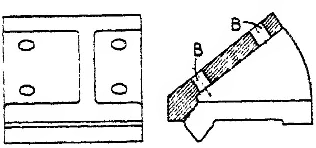


FIG. 208.

From the above description, it should be clear that *the chief function of a jig is to guide the cutting tool.* The chief function of a *fixture*, however, is to *hold the work while it is being operated on* or to make the holding easier than it otherwise would be. As a simple example of a fixture, consider the job shown in Fig. 208. The bottom surfaces have been machined and it is required to drill the holes B

so that they are accurately perpendicular to the inclined face. A fixture such as is shown in Fig. 209 might be used ; this brings the face C horizontal and enables the drilling to be done easily. The fixture is machined at E and F to take the work and at G to bear on the drilling machine table, while a clamp plate H is provided to hold the work to the fixture. If this fixture is extended over the top of the work, as indicated by the chain dotted lines, and if bushes are provided to guide the drills, it becomes a *jig fixture.* The term jig alone is, however, commonly used, and is used in what follows, to denote not only true jigs as defined above, but also jig fixtures and, sometimes, pure fixtures.

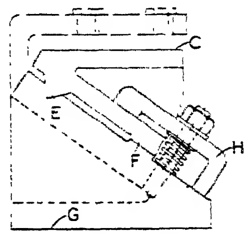


FIG. 209.

Jigs are used extensively in quantity production but more with drilling and boring machines than with other types. Fixtures, however, are extensively used with all types of machine because the problem of holding the work arises with all machines. Whether a jig shall or shall not be used for any particular operation will depend chiefly on the cost of the jig itself and on the number of pieces of work that are to be produced. Sometimes the use of a jig is imperative in order that the articles produced shall be interchangeable, but the tendency now, when small quantities of interchangeable pieces are required, is to machine them on jig-boring machines which can give the required accuracy without the use of jigs. When rigid interchangeability is not essential and the quantity required is not sufficiently large to justify the expense of a jig, then the pieces will be " marked out " for the guidance of the operator and the accuracy of spacing of holes will be obtained by the methods described in the previous chapter. The marking-out process is considered below.

Boring jigs usually provide support for both ends of the boring bar, as shown in Fig. 210, and in order to eliminate any trouble from misalignment of the jig and the spindle of the boring machine, the boring bar is connected to the spindle by a short intermediate shaft fitted with a universal joint at each end.

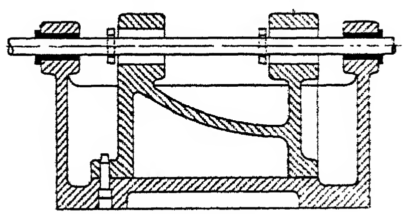


FIG. 210.

The surfaces of jigs that are subject to wear due to the putting in of the work are sometimes reinforced with hardened steel or cemented carbide strips.

A few examples of jigs and fixtures are shown in Figs. 211–213.

Generally speaking a jig is designed for a particular operation in a

particular machine and it remains with that machine, the work coming to it and, after the operation has been performed, passing on to the next machine which may employ another jig. When this procedure is adopted the piece of work will, so far as is possible, be located in all the various

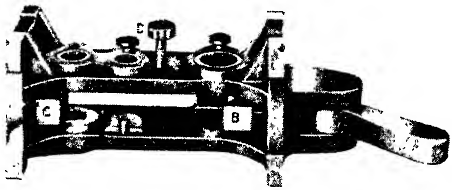


FIG. 211.

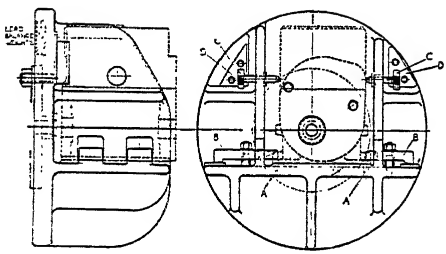


FIG. 212.

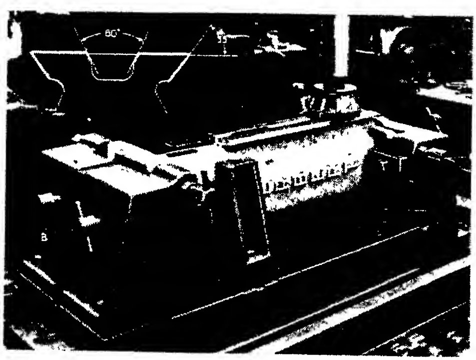


FIG. 213.

jigs by means of the same surfaces, since by this means cumulative errors are avoided. The choice of the most suitable locating surfaces is a matter of great importance.

An alternative way of using a jig is to let it travel with the work from machine to machine until all the operations have been done and the work

can be removed and the jig sent back to the first machine of the series to receive a fresh piece of work. When this system is employed a number of similar jigs will have to be provided so that all the machines can be kept working; the minimum number would be one greater than the number of machines. The jigs are arranged so that they can quickly be located on the work tables of the machines and they may be provided with wheels so that they can be moved along runways from machine to machine. Such jigs are only used in large quantity production schemes

Jig-boring Machines. Since the accuracy of a piece of work that has been produced by means of a jig cannot be greater than the accuracy of the jig itself, it is important that the jig should be made to a high degree of accuracy. Generally speaking the permissible errors in the jig will be only about one-tenth of those permissible in the work. In order to achieve this accuracy specially accurate jig-boring machines have been developed in which the greatest care has been taken both in the design and construction to promote accuracy. Thus the castings used in

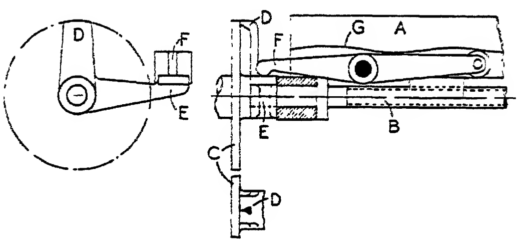


FIG. 214.

these machines are always kept for considerable periods before they are rough machined and then again before they are finish machined, in order to allow the castings to " age," and to eliminate all internal stresses that might subsequently cause distortion; or the same results are produced by appropriate heat treatment. The fits of the various parts of the machine are closer than in normal machine tool practice and special methods are used to enable the movements of the work table, spindle heads, etc., to be accurately measured. These special methods are three in number. They are: (1) The use of a compensated lead-screw; (2) The use of fixed end gauges; and (3) The use of engraved scales read by means of microscopes. The principle of the first method is shown in Fig. 214.

The work table A is moved by a lead-screw B which carries a graduated dial C. The index mark against which this dial is read is not, however, fixed but is marked on one arm D of a bell-crank lever, the other arm E of which is actuated through a lever F pivoted on a fixed pivot, by a cam-plate G fixed to the work table A. The contour of the cam-plate is

scraped by hand to compensate for the errors of the lead-screw so that the movement of the work table is the movement indicated by the dial. The principle of the second method is indicated in Fig. 215. The work table A is traversed by a lead-screw and nut in the ordinary way but its movements are measured by means of end-gauges (see Chap. 21) B which are supported in a trough C between an anvil D carried by the work table and a moveable anvil E carried by a fixed part of the machine. The anvil E actuates a sensitive indicator F and enables the end pressure exerted on the gauges to be made always the same. To obtain any required movement of the work-table, gauges, length L_1, are placed in the trough and the table is moved until the indicator F reads zero. The gauges are then replaced by others whose length is L_2 where $L_1 - L_2 =$ the required movement of the table, and the latter is moved until the indicator F again reads zero. The accuracy obtainable by this method depends largely on the sensitivity of the indicator F, but it can give more accurate results than the compensated lead-screw method can give. The third method is the one used on the latest model jig-boring machine made by the Société Genevoise, whose machines have a world-wide reputation for accuracy. This machine will now be briefly described.

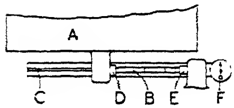


Fig. 215.

The S.I.P. Jig-Borer. The general appearance of this machine is shown in Fig. 216. The work table B is carried on ways machined on the massive bed A and can move to and fro underneath the spindle C. The latter is carried in a saddle D which can be moved, at right angles to the bed ways, along the beam E which is adjustable vertically on the columns F to accommodate various heights of work. The relative positions of holes and surfaces are obtained by means of two adjustments: (*a*) of the work table along the bed, and (*b*) of the saddle across the beam, and on the accuracy with which these can be made will depend the accuracy of the work. The actual movements are made by hydraulic means for the work table, and by a screw for the saddle, but the measurement of the movements is done by means of scales, engraved on alloy steel, which are fixed respectively to the work table and saddle. These scales are observed by means of microscopes G and J built into the bed and beam structures respectively. Graduated drums H fitted with verniers are used to get the adjustments approximately right and the final adjustment to the nearest 0·0001 in. is obtained by getting coincidence between a graduation on the scale and an index line in the eyepiece of the microscope. The steel scales are enclosed in hermetically sealed chambers to prevent the ingress of dust and moisture and thus the initial accuracy is retained indefinitely The spindle is provided with eighteen different speeds and a number of vertical feeds and the machine is capable of doing milling work as well

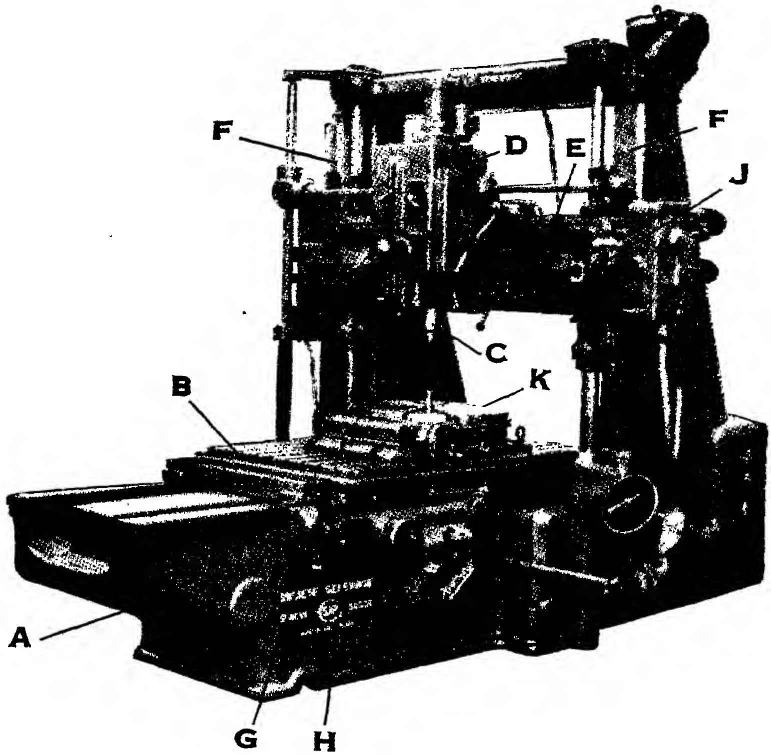


Fig. 216.

as drilling and boring. A circular table K increases the versatility of the machine.

Marking Out. The marking-out or setting-out process consists, briefly, in marking or scribing sufficient lines on each piece of work, casting, forging, etc., to guide the machine operator in the subsequent operations of setting up the work in the machines and in the actual machining. In many cases the accuracy of the work depends directly on the accuracy of the marking out, but frequently the latter is merely an indication of the necessary machining and the accuracy is determined by means of the adjustments of the machines and by the use of gauges in making the machine settings.

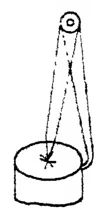


Fig. 217.

Perhaps the simplest marking-out operation is the centering of a circular bar by means of a pair of hermaphrodite or odd-leg callipers; as indicated in Fig. 217 the callipers are set to the approximate radius of the bar and, with the calliper leg held against the edge of the bar at three equidistant points, three arcs are drawn; the centre dot or pop marking the centre of the

bar can then be put in the centre of the resulting triangle by eye or, alternatively, the callipers can be readjusted until the three arcs intersect in a point.

Another simple marking-out operation is the marking out of the positions of a number of holes which are to be drilled. The centre of each hole is marked by a centre pop and a circle is scribed to represent each hole, the diameter of the circle being made equal or slightly larger than the actual size of the hole. The circles, after being scribed, are usually centre-popped in four or more places in case the scribed line is effaced.

In order to render the marking-out lines more easily visible, it is common practice to whitewash castings, forgings, etc., either all over or, more usually, just where the lines are to be placed. Lines on machined surfaces are made visible by rubbing the surface with a slightly acid solution of copper sulphate (blue vitriol), a thin deposit of copper resulting.

The marking out is generally done on a large surface plate or marking-out table whose surface is accurately flat and level and the chief instruments used are scribing blocks, vernier calliper gauges of the type shown in Fig. 311, dividers (both ordinary and beam type), set-squares, levels, and clinometer. The casting, forging, or other piece of work may be clamped to a box square if it is fairly small or may be supported on packing blocks, jacks, etc., if it is large. The cored holes of castings must be blocked by suitable pieces of plate wedged in and on whose surface the centre of the hole can be marked in order to enable the marking-out circle to be drawn with the dividers.

In the marking out of castings and forgings, the marker out has to allow for the variations between the actual casting and one corresponding exactly to the drawing. For example, the casting shown in Fig. 218, when marked out, will have a line X round the base to indicate the machined lower surface and circles Y and Z to delineate the holes. If the line X were put in so that the thickness of the base t was right, without any further consideration, it would probably be found that when the circles Y and Z were scribed they would be somewhat eccentric to the outsides of the bosses. By varying the thickness t, which is not a very critical dimension, the circles can be brought more closely concentric with the bosses and the marker out must effect the best compromise possible.

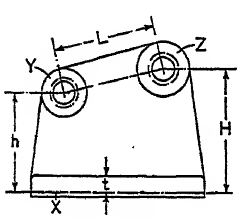


Fig. 218.

The marking-out process is simplified, when a number of pieces have to be done, by the use of sheet steel templates.

Chapter 15

THE MILLING PROCESS, CUTTERS, AND MACHINES. THE DIVIDING HEAD

The milling process is very widely used and is second in importance only to the lathe. Essentially it consists of the use of a rotating cutter against which the work is fed as indicated in Fig. 219. The speed of rotation of the cutter is chosen so as to give a peripheral speed suitable for the material being cut, the type of cutter, the depth of cut, the rigidity of the work, and the machine used, etc. This speed may range from as low as 10 ft. per minute up to as high as 2,000 ft. per minute. The feed motion is comparatively slow, ranging from a few inches per minute up to about 25 in. per minute.

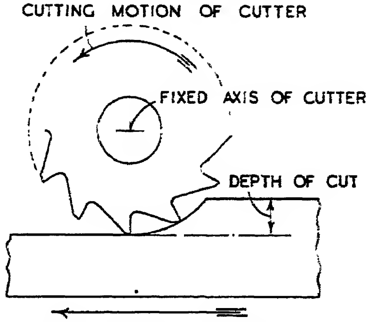


FIG. 219.

The Nature of the Cut Taken. A little consideration will show that the path of the cutting edge of a tooth, relative to the work, is a looped curve, actually a trochoid, as shown in Fig. 220, and that the metal removed by the cutting edge in travelling from P to P_1 is as shown cross-hatched. In the diagram the travel of the axis of the cutter per revolution has been greatly exaggerated, and the cutter has been assumed to have only one tooth. The surface of the work is seen to be left with a series of hills and valleys, but it will be realised that with the feeds that are actually used and with cutters having many teeth the height of the " hills " is extremely small, being in fact unmeasurable except with extremely delicate apparatus. The shape of the chip produced in practice is as shown in Fig. 221 and the thickness varies from nothing at the point P, where the surface of the work is finished, up to t at the end

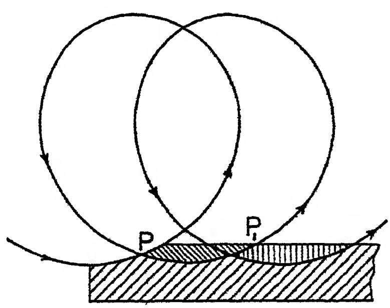


FIG. 220.

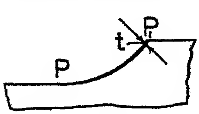


FIG. 221.

P_1; because the chip thickness where the surface of the work is finished is small it is possible with the milling process to take very deep cuts and yet obtain relatively excellent surface finish.

An enlarged section of an ordinary milling cutter tooth is shown in Fig. 222. The face of the tooth is sometimes made radial but nowadays is more usually given a definite cutting rake and typical values for the angle α are given below. The clearance angle β ranges from 3 degrees in cutters for hard steels up to 8 degrees in cutters for light alloys; 6 degrees is a common value. The width of the *land L* varies with the size of the cutter and is from about $\frac{1}{32}$ in. in small cutters up to $\frac{3}{32}$ in. in large ones. Since the cutters are sharpened by grinding the land, the width gradually increases. The space between the teeth has to accommodate the chip as it is removed during the passage of the cutting edge past the work. It is important that adequate chip space should be provided for, otherwise the cutter will not cut properly; reduction of chip space due to repeated sharpening of the cutter is often the factor that determines the end of the useful life of the cutter.

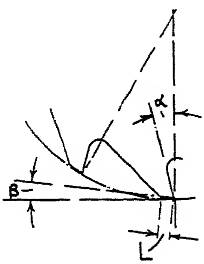


FIG. 222.

Material	*Angle α degrees*	*Angle β degrees*
Steel 30–40 t.s.i.	20	7
„ 40–50 „	15	5
„ 50–60 „	10	4
C.I.	15	6
Copper	20	6
Brass	20	6
Bronze	15	5
Light alloys	25	8

The Horizontal Milling Machine. This is made in several types, one of the commonest being the knee type shown in Fig. 223. This consists essentially of a massive column casting A which is provided with bearings for the spindle B and which houses the driving motor and the gearboxes that provide the various speeds to the spindle and feeds to the knee, saddle, and work table. The face of the column is accurately machined perpendicular to the spindle axis and carries the *knee* casting C, the top face of which is machined to take the *saddle* F. The top of the saddle is machined to take the *work table* H. The knee assembly can be raised or lowered by means of a jack-screw D arranged underneath it and operated by the handle E or by power. The saddle can be moved on the knee and the work table on the saddle by means of screws and nuts either by hand by turning the handles G or J, respectively, or by power. The mandrels or arbors that carry the cutters fit into a taper hole in the spindle and are held in place by a draw-bolt that passes through the spindle; a positive drive is ensured by means of driving keys such as can be seen in the illustration or by similar means. The

cutters are positioned on the mandrels by means of spacing pieces, are driven by a key, and are held on the mandrel by a nut on its outer end. A steady arm L serves to carry a bearing bracket to support the outer end of the mandrel and intermediate supports can sometimes be arranged as shown. While a cut is being taken the knee is clamped to the column and, if the cut is at all heavy, to the steady arm also by means of the brace M shown. In some machines the front of the knee can be clamped to the base of the frame during cutting. These clamps must be released when it is desired to raise the knee in order to adjust the cut. In manufacturing work it is common practice to get down to the finished size in

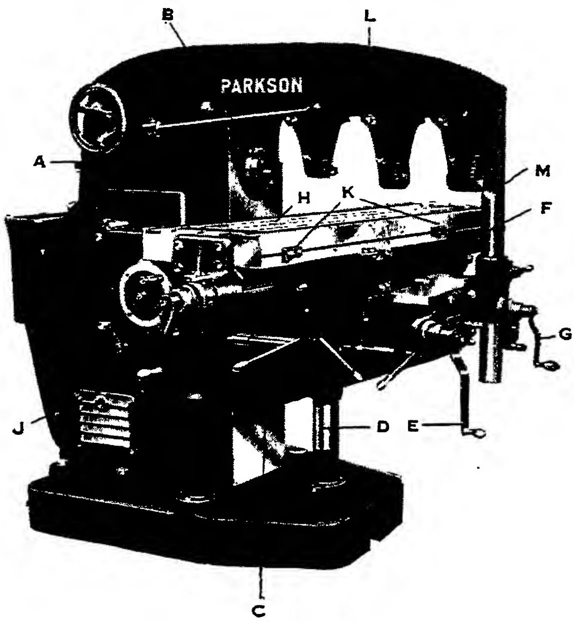


FIG. 223.

a single cut, but in general work two or more cuts will be taken. The saddle can be clamped to the knee and the work table to the saddle, when required. Adjustable dogs K provide an automatic disengagement of the power feed to the work table and similar dogs are provided for the saddle and knee motions.

Types of Cutter. Milling cutters are made in a large variety of shapes but they may be roughly divided into cutters for horizontal machines and cutters for vertical machines (in which the spindle axis is vertical, as will be seen later). They may also be divided into *ordinary* cutters and *relieved* cutters; the essential difference between these will be dealt with later. The majority of horizontal milling machine cutters are used on a

mandrel and consequently have a central hole. Examples are seen in Fig. 224, A–H. The cutter A is a *shell* or *slab* milling cutter and is a widely used type; it has helical teeth because these give a smoother cutting action than straight teeth parallel to the axis, but straight-toothed

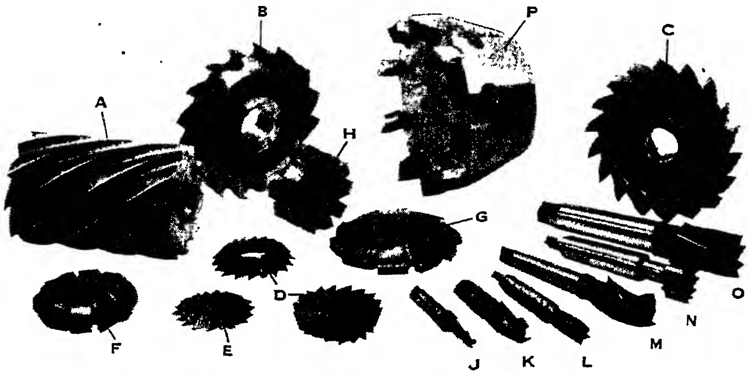


FIG. 224.

cutters are used. At B is seen a *slot-milling* cutter and at C a *side-and-face* cutter. *Angular* cutters are seen at D and E, while at P there is a *face* cutter; this is mounted direct on the nose of the machine spindle and operates on the vertical side face of the work in a horizontal machine and on the horizontal top face of the work in a vertical machine.

Gang Milling. In this a number or gang of cutters, of different diameters, lengths, and shapes, is mounted on a mandrel as shown in Figs. 225 and 226 so that the surface of a piece of work can be brought

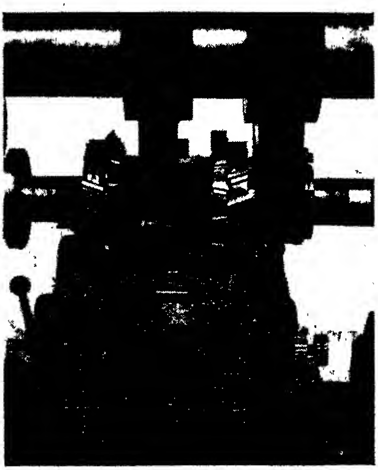


FIG. 225.

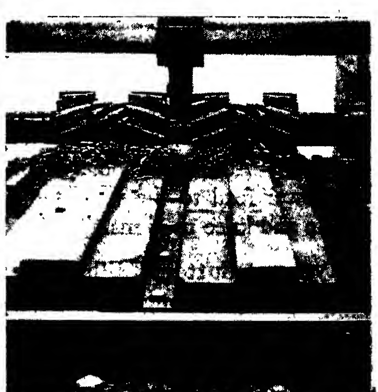


FIG. 226.

to the required shape in one pass underneath the cutters. The gang of cutters is sometimes kept mounted on its mandrel in the tool store in readiness for each batch of work as it comes along, but this may involve the uneconomic locking up of the capital represented by the cutters Care has to be observed in the grinding of ganged cutters so as to maintain the proper profile on the work. Fig. 227 shows some typical profiles machined by gang cutters with particulars of the work, cutters, speeds. and feeds.

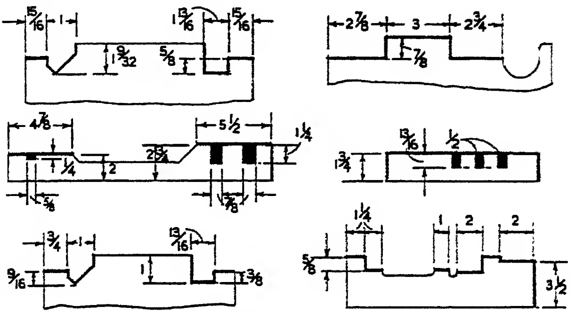


FIG. 227.

1. Material—Cast Iron, Brinell 212
   Spindle speed—21 r.p.m.
   Dia. of largest cutter—10·5 in.
   Max. cutting speed—58 ft. per min.
   Feed—4 in. per min., 0·19 in. per rev.
2. Material—Steel, Brinell 207
   Spindle speed—21 r.p.m.
   Dia. of largest cutter—10·5 in.
   Max. cutting speed—58 ft. per min.
   Feed—1·25 in. per min., 0·06 in. per rev.
3. Material—Cast Iron, Brinell 212
   Spindle speed—32 r.p.m.
   Dia. of largest cutter—6·5 in.
   Max. cutting speed—55 ft. per min.
   Feed—2·44 in. per min., 0·076 in. per rev.

1. Material—Cast Iron, Brinell 212
   Spindle speed—21 r.p.m.
   Dia. of largest cutter—6 in.
   Max. cutting speed—33 ft. per min.
   Feed—2·5 in. per min., 0·119 in. per rev.
2. Material—Steel, Brinell 207
   Spindle speed—25 r.p.m.
   Dia. of largest cutter—8·5 in.
   Max. cutting speed—56 ft. per min.
   Feed—1·25 in. per min., 0·05 in. per rev.
3. Material—Cast Iron, Brinell 212
   Spindle speed—21 r.p.m.
   Dia. of largest cutter—10·5 in.
   Max. cutting speed—58 ft. per min.
   Feed—2·5 in. per min., 0·119 in. per rev.

The Lincoln or Manufacturing Type of Machine. For heavy manufacturing work the knee type of construction is not always rigid enough and the *Lincoln* or *manufacturing* type of machine shown in Fig. 228 is then used. The work table slides on the top of the bed which is carried directly on the foundations and the distance between the spindle axis and the table is adjusted by moving the head that carries the spindle up or down the column of the machine. The machine shown has only one spindle head, but by providing a second column a second spindle

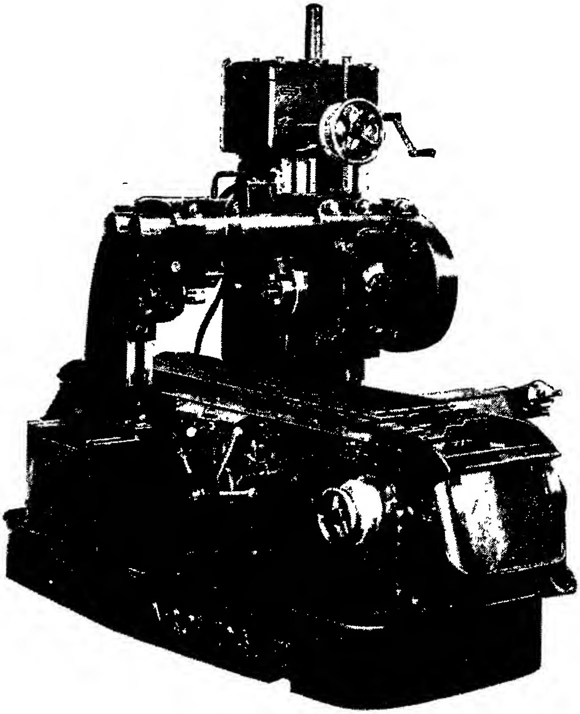


FIG. 228.

head can be arranged opposite the first. This enables a large gang of cutters to be driven from both ends or enables two face cutters to operate on the two sides of a piece of work simultaneously. This type of machine is not so convenient for general work as the knee type.

Methods of Holding the Work. One common method is in a vice which is bolted to the work table and special quick-acting vices are made for the purpose. The jaws of most vices tend to lift slightly as the vice is tightened up and a piece of work A, Fig. 229, which rests on a pair of parallel strips BB before the vice is tightened up will generally not be in contact with the strips after tightening. The work must be brought down on to the strips again by hitting it with a lead hammer. To reduce the tendency to lift to a minimum, machine vices are made with movable jaws that have very long bearing surfaces on the vice body. A second method is by clamping direct to the work table by means of clamping bolts and plates and it is generally desirable to put a driving plate, as shown in Fig. 230, at the end of the work to make the feed positive if

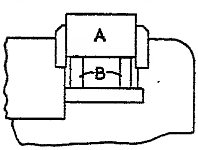


FIG. 229.

a heavy cut is to be taken. Bent or inclined holding down plates, as shown on the right in Fig. 230, are useful when holding down plates cannot be arranged on the top of the work. When the quantity of work is fairly large, specially designed work-holding fixtures are used and these are sometimes made double-ended so that a piece of work may be put into one end while the piece at the other end is being machined. Cylindrical work such as shafts, twist drills, reamers, milling cutters, etc., is generally most conveniently held between centres and as such work frequently has to have a number of flats, key-ways, gashes, or grooves milled in them, they are conveniently held at one end by an *indexing* or *dividing* head and at the other end by a tailstock as shown in Fig. 231.

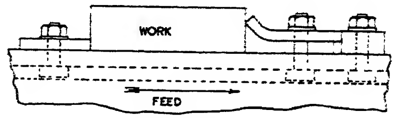


FIG. 230.

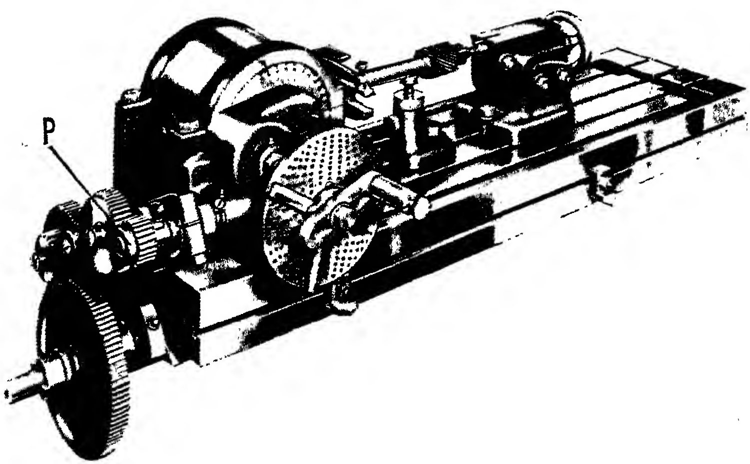


FIG. 231.

The dividing head enables the grooves, etc., to be spaced at the proper angular distance apart, as will be described in the next article. Work that is at all frail must be supported by packing pieces arranged underneath it, or by small screw-jacks as shown in Fig. 231. It is sometimes necessary, with flimsy cover plates, for example, to have special holding lugs cast on, these being removed when the machining is finished.

Indexing or Dividing Heads. The simplest dividing head consists of a casting that carries a horizontal spindle which at one end is provided with a centre and driving plate and at the other end with an *index plate*. The latter is a circular plate in the circumference of which is cut a number

of equally spaced wedge-shaped grooves. The casting carries a spring-loaded plunger or latch which engages the grooves in the index plate. The index plate thus enables the spindle and work to be turned through equal angles whose value depends on the number of grooves in the index plate. Thus a piece of work may be " divided " into any number of divisions that is a sub-multiple of the number of grooves in the index plate. The spindle can usually be clamped independently of the indexing latch or plunger in order to relieve the latter of undue stress. Such indexing heads are used for commonly occurring work in which the number of divisions is not greater than about thirty-two. For general work a universal dividing head is used and the general form of this is indicated in Fig. 232. It consists of a short spindle A screwed at one end to take a chuck or driving plate and bored to take a centre and having a worm-wheel B fixed to it inside the casing. A single-thread worm C meshes with the worm-wheel and a handle D is geared to the worm shaft. The

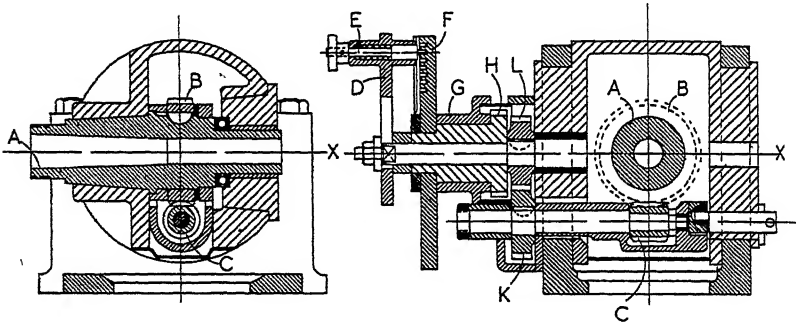


FIG. 232.

handle D is slotted so that a spring plunger assembly E may be adjusted to any radial position along it. The end of the spring plunger can engage holes formed in the *dividing plate* F. The latter is a circular plate in which have been accurately drilled a number of circular rows of holes, each row having a different number of holes. The dividing plate is attached to a short shaft carried in the boss G and can be locked to the casing when required but which can also be driven by the gear H from a short shaft P, not shown in the figure, whose axis is horizontal and perpendicular to that of the worm-shaft. By gearing the shaft P to the lead-screw of the work table on which the dividing head is mounted, as seen in Fig. 231, the rotational motion of the spindle A can be correlated to the linear travel of the work table and dividing head. Supposing the wheel H, and thus the plate F, to be fixed then by disengaging the plunger E and turning the handle D until the plunger can be re-engaged in the adjacent hole, the handle D will be turned through an angle whose value depends on the number of holes in the particular row of holes being

used. Supposing that number to be n, then the angle would be $\frac{360}{n}$ degrees. If the gear ratio of the worm and wheel is 1 to x, then the angle turned through by the spindle A would be $\frac{360}{nx}$ degrees. If, instead of engaging the plunger in the adjacent hole, it had been moved past several holes and engaged with the Nth hole from the starting hole (which is reckoned as number 0) then the angle turned through by the spindle A would have been $\frac{N \times 360}{nx}$. Now x is almost always made equal to 40, hence usually the angle turned through by the work is given by $\frac{N \times 9}{n}$ and n is the number of holes in the row being used and N is the number of holes, or better, spaces, traversed by the plunger in the row. By choosing N and n suitably almost any angular movement may be obtained. The accuracy of the movement of the spindle will depend on the accuracy of the spacing of the holes of the dividing plate and the accuracy of the worm and wheel. Precautions, as described on p. 165, must be taken to eliminate the effects of backlash. To obviate having to count the number of spaces traversed by the handle D at each indexing a simple measuring device is used; it consists of a pair of arms A and B (Fig. 233) the angular distance between which can be adjusted and which can then be locked together. The assembly is a light friction fit on a boss on the dividing plate and when an indexing motion is to be made it is turned round until the arm A comes up against the plunger E; the latter is then turned until it comes opposite the hole X, which is indicated by the arm B.

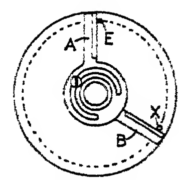


FIG. 233.

In most dividing heads supplied with universal milling machines the spindle A can be tilted about the axis XX (Fig. 232) so as to make any angle from 0 to 90 degrees with the horizontal. This enables such jobs as the angle cutters shown at D in Fig. 224 to be milled.

A tailstock is always supplied with a dividing head so that work can be held between centres. The means used to connect the work to the spindle must be such as to hold the work against either forward or backward rotation; one driving arrangement is shown in Fig. 234. The carrier A is secured to the work

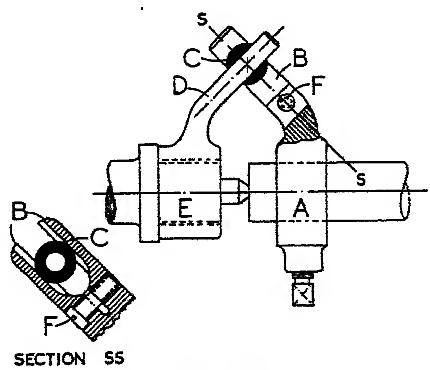


FIG. 234.

and its forked end B engages a ball C which is a sliding fit on the arm D of the driver E, which is mounted on the spindle nose of the dividing head. The two arms of the fork B can be drawn together by a screw F so as to eliminate any play. This arrangement permits the axis of the work to be out of alignment with the spindle axis, if that is required, while ensuring that the work turns through exactly the same angle as the spindle.[1]

Compound Indexing. In some dividing heads the plate F (Fig. 232) can be left free relatively to the body and be positioned by a second spring plunger, carried by the body and entering the holes of the dividing plate from the back. This enables the handle D to be given a compound motion; it being first moved forwards, by disengaging the plunger E and turning it, the plate F being stationary, and then moved either forwards or backwards by disengaging the back plunger and turning the plate and handle D together. Let n be the number of holes in the row engaged by the plunger E and let N be the number of spaces traversed by that plunger in the first motion. Let m be the number of holes in the row engaged by the back plunger and M the number of spaces traversed by that plunger. Then the motion of the spindle A is given by

$$\theta=\frac{360}{40}\times\left(\frac{N}{n}\pm\frac{M}{m}\right)=9\left(\frac{N}{n}\pm\frac{M}{m}\right)$$

the plus or minus sign being used according as to whether the second component motion is in the same direction as the first motion or is in the opposite direction. This method of indexing enables some divisions to be obtained which would be impossible by the ordinary method with standard dividing plates. It is, however, little used now, having been replaced by a better method which will now be dealt with.

Differential Indexing. In this process the shaft H, Fig. 232, that carries the dividing plate F, is geared to the spindle A so that as the handle D is revolved, and the spindle A is turned, the plate F is moved in a direction which is either the same as or is the opposite to that of the handle D according to the arrangement of the gearing. The resultant motion of the spindle is then equal to one-fortieth of the algebraic sum of the motion of the handle D relative to the plate, and the motion of the plate F relative to the body of the dividing head. Suppose the gear ratio between the spindle A and the shaft H is p, that is, one revolution of A would produce $\frac{1}{p}$ revolutions of H, and suppose the gear train to be such that the plate F turns in the same direction as the handle D when the latter is turned. Then if n is the number of holes in the row engaged by the plunger E and N the number of spaces traversed in that

[1] See the author's "Mechanism and the Kinematics of Machines," p. 279.

row, the motion of the spindle A will be given by $\theta=\frac{360Np}{n(40p-1)}$ degrees. This result is easily proved as follows. Let the motion of the spindle A relative to the body be θ degrees. Then the motion of the plate F, also relative to the body, will be $\frac{\theta}{p}$ degrees. But the motion of the arm D relative to the plate F is $\frac{360N}{n}$ degrees. Hence the motion of the arm D *relative to the body* is $\frac{360N}{n}+\frac{\theta}{p}$. Hence the motion of A relative to the body is $\frac{1}{40}\left(\frac{360N}{n}+\frac{\theta}{p}\right)$, but this is equal to θ.

Hence $$\theta=\frac{1}{40}\left(\frac{360N}{n}+\frac{\theta}{p}\right)$$

$$\therefore \qquad \theta\times\left(1-\frac{1}{40p}\right)=\frac{9N}{n}$$

$$\theta=\frac{360Np}{n(40p-1)}$$

$$\therefore \text{ Number of divisions } \left(=\frac{360}{\theta}\right)=\frac{n(40p-1)}{Np}$$

Optical Dividing Heads. Some years ago the Zeiss company introduced a dividing head in which the spindle A (Fig. 232) carried an accurately divided scale, a microscope being provided to enable the scale to be read accurately. No index plate is used, the motions given to the spindle being read directly off the graduated scale. This dividing head was considerably more accurate than any ordinary dividing head. Optical dividing heads are now made by Messrs. Cooke, Troughton and Sims, Ltd., of York, and by other makers.

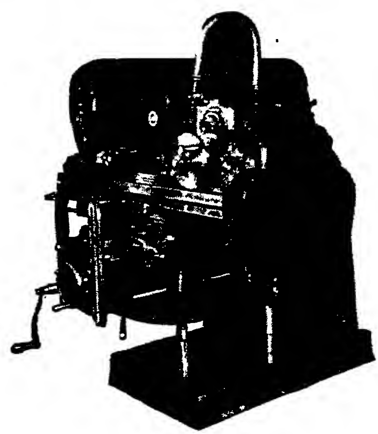


FIG. 235.

The Universal Horizontal Milling Machine. This is very similar in general arrangement to the plain type of machine shown in Fig. 223, as will be seen from Fig. 235, the principal difference being that the saddle is made in two parts and the top part, carrying the work table, can be swung around about a vertical pivot relative to the bottom part, so that the direction of the travel of the work table can be at other angles than

90 degrees to the spindle axis. This enables helical grooves to be milled, which is not possible on a plain machine, in which the work table travel is set permanently at 90 degrees to the spindle axis. In some machines the knee can also be swivelled about a horizontal axis, parallel to the spindle axis. Vertical milling attachments which convert the horizontal machine into a vertical one (see p. 239) are also commonly supplied with universal machines.

Milling a Helical Slot. Suppose it is required to cut a helical slot, such as the flute of a twist drill, in a cylindrical bar. The procedure is as follows: the dividing head is mounted on the end of the work table and its shaft H (Fig. 232) is geared to the work-table lead-screw, as seen in Fig. 231, the gear ratio being determined as is explained later. Generally a compound train of gears will be required and the intermediate gears are carried on an arm which is arranged to fit over the boss of the work-table lead-screw bearing. The work is mounted between centres as shown. If now the lead-screw is rotated then the work table will travel along and, simultaneously, the work will rotate. A fixed pointer would therefore trace out a helix on the surface of the work.

Let the gear ratio of the gearing connecting the lead-screw to the dividing head be k, that is, let the ratio

$$\frac{\text{R.p.m. of shaft H}}{\text{R.p.m. of lead-screw B}}=k$$

and let the number of threads per inch in the lead-screw be s. Then, since the gear ratio between the shaft H and the spindle of the dividing head is 40 to 1, one revolution of the lead-screw would rotate the work $\frac{k}{40}$ revolutions and, simultaneously, would traverse the work table $\frac{1}{s}$ in. Hence the work table will travel $\frac{1}{s}\times\frac{40}{k}=\frac{40}{sk}$ inches for one revolution of the work and this is consequently the lead of the helix traced by the pointer. If the diameter of the bar upon which the helix is traced is d inches, then the spiral angle α of the helix (the angle between the axis of the bar and a tangent to the helix at any point) is given by

$$\text{Tan}\,\alpha=\frac{\pi d}{\text{Lead}}=\frac{\pi dks}{40}$$

Example. Let the lead of the helix $=7{\cdot}5$ in.
diameter of work $=2{\cdot}5$ in.
No. of threads per inch in lead-screw $=4$.

Then
$$7{\cdot}5=\frac{40}{4k}=\frac{10}{k}$$
$$k=\frac{4}{3}.$$

Hence the gear ratio between lead-screw and dividing head must be 4 : 3 and a 40-tooth wheel might be used on the lead-screw and a 30-tooth wheel on the shaft H. An intermediate wheel may have to be used to make the " hand " of the helix correct.

Then $$\tan \alpha = \frac{\pi \times 2{\cdot}5}{7{\cdot}5} = 1{\cdot}0472$$

$\therefore$ $$\alpha = 48^\circ\ 6{\cdot}5' \text{ approx.}$$

The work table must be swung around on the swivel until the plane of the cutter makes this angle α, with the axis of the work, as is indicated in Fig. 236. The shape of the groove cut, as seen in a cross-section by a plane perpendicular to the tangent to the helix, will then be the same as the shape of the cutter as seen in a cross-section by a plane containing its axis, unless " interference " occurs. What is meant by " interference " will best be understood by considering what would happen if an attempt were made to cut a helical groove having a section as in Fig. 237, *a*. The corners of the cutter at X and Y (*b*) would cut away the sides of the groove so that the shape of the groove would be somewhat as shown at *c*. This is known as interference and is due, of course, to the fact that the helix curves off to right and left, while the cutter is necessarily " straight " or plane. It is consequently impossible to mill a helical groove with a rectangular cross-section, but with semicircular grooves interference seldom occurs.

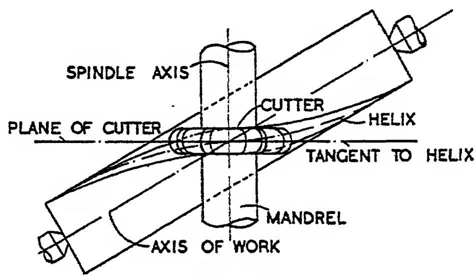


FIG. 236.

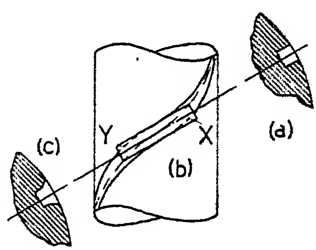


FIG. 237.

When one groove has been milled the work may be indexed round through any desired angle by disengaging the spring plunger of the dividing head handle and turning that handle the appropriate amount. A locking device is provided to lock the dividing head spindle but this, of course, cannot be used when milling a helix. In determining the helix angle different results will be obtained according to whether the diameter *d*, in the formula developed above, is taken to be the diameter at the top or bottom of the groove, and, since the cutter cannot be set at both angles simultaneously, it is generally set at the angle given by using the mean diameter of the groove, i.e. half the sum of the top and bottom diameters.

Relieved or Form Cutters. Cutters whose outline is wholly or partly curved cannot conveniently be sharpened if they are made like the cutters described on p. 228; instead they are made by a relieving process and the difference between them and ordinary cutters will best be understood by considering the principle underlying the making of a relieved cutter. Suppose a semi-circular cutter such as is shown at F, Fig. 224, is required. A lathe tool on the lines of Fig. 238, *a*, will first be made and by its means the cutter blank will be turned up to the shape shown in Fig. 238, *b*. This blank, on the mandrel on which it was turned, will then be transferred to a milling machine and will be gashed as shown at *c*, all the faces of the gashes being made radial, as shown. The gashed blank will then be mounted, still on its mandrel, in a *relieving lathe*, and the original tool used for turning the blank will be mounted in the tool post. The slide rest of the relieving lathe has a cam A (Fig. 239) which is connected by shafts and gearing to the lathe spindle so that as the spindle, and thus the gashed blank, is rotated the tool is given an in-and-out motion and the blank is ultimately formed to the shape shown. The principle of the process is indicated, quite diagrammatically, in Fig. 239. The gearing connecting the cam A to the spindle must be such that the cam shown makes one revolution while the work turns through the angle θ. Actually a face cam having three or four " rises " is generally used and in that case the gearing must be such that the cam does $\frac{1}{n}$ revolutions while the work turns through θ degrees, n being the number of " rises " of the cam.

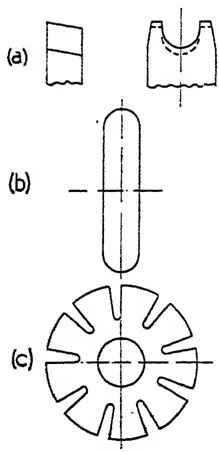


Fig. 238.

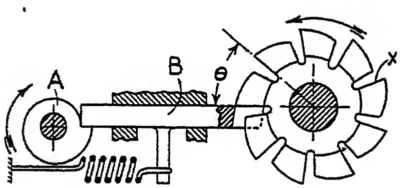


Fig. 239.

The top face of the tool, that is, the plane containing the cutting edge of the tool, must be arranged so that it always passes through the axis of the work. The result is that any section of a tooth of a cutter made by this process will, provided the plane of the section contains the axis of the cutter, have the same outline as that of the tool used to form the cutter. Relieved cutters must consequently be sharpened by grinding the faces X (Fig. 239) and care must be taken to grind those faces so that they are truly radial, i.e. pass through the axis of the cutter. Relieved cutters are seen at F, G, and H in Fig. 224.

The Vertical Milling Machine. This differs from the horizontal machine chiefly in that the spindle axis is vertical instead of horizontal. Vertical milling machines are made in several forms; the smaller sizes are generally of the knee type as shown in Fig. 240 and the knee, saddle, and work table components are frequently interchangeable with the corresponding horizontal machines made by the same maker. The column casting is, however, adapted to the vertical position of the spindle. The latter is carried in a head which is adjustable vertically on a machined face on the column and this adjustment is used to "put on the cut" so as to bring the work to the correct size, the knee being moved only to allow for work of different heights. In some machines the slide carrying the spindle head can be swivelled about a horizontal axis perpendicular to the knee-ways. This enables the spindle axis to be at any angle to the work-table surface and increases the versatility of the machine.

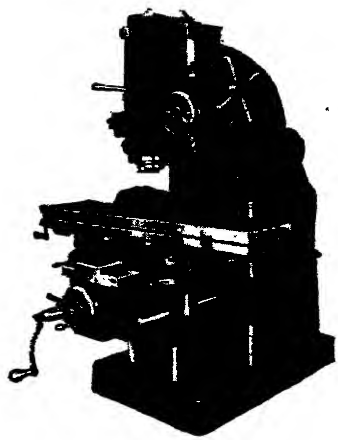


FIG. 240.

The cutters used in vertical machines are almost invariably of the type shown in Fig. 224, J–O, and cut on the sides and ends; they are consequently overhung from the spindle when in use; they have tapered shanks to fit the taper hole in the spindle, adaptor collets, or sleeves being used with the smaller sizes. The cutters are held in the spindle by various means but usually they are secured positively and not merely by friction.

The vertical milling machine can machine a flat surface either by using a relatively small diameter cutter and traversing the work under it several times, the saddle being fed across an amount slightly less than the cutter diameter between each traverse, or by using a cutter of the type shown in Fig. 224 at P whose diameter is greater than the width of the work and traversing the work under the cutter only once. The latter is the more efficient method and can compete, in the matter of time required to remove a given quantity of metal, with the horizontal machine of equivalent size. The vertical machine is, however, chiefly used for

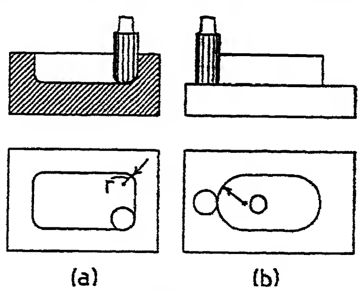


FIG. 241.

work that cannot be done on other machines; for example, any non-circular projection or recess as indicated in Fig. 241. Clearly the radius of the cutter used for the final cut when machining a recess cannot be greater than the radius *r* of the corners of the recess. It should also be quite obvious that a milling cutter cannot machine an internal corner that is not rounded off—a point that should be borne in mind by designers. External corners, and internal ones too when their radius is large, may be milled in two ways. In the first, which is used when the profile of the corner is not required to be very accurate, the profile is obtained by operating the work table and saddle traverse mechanisms simultaneously, by hand usually. The second method is used for profiles made up of circular arcs and straight lines and involves the use of a *circular table* (an example being shown in Fig. 216, p. 223). This is a table, arranged with the usual T-slots to accommodate holding-down bolts, which can revolve about a vertical axis; the work, say that shown in Fig. 241, *b*, is set up on the circular table so that the axis of rotation of the table coincides with the axis, O, of the profile to be milled. This is done by a "sticky-pin" method analogous to that used to set up work in the lathe and boring machine and described on p. 213. The table is then revolved, either by hand or power, to give the feed.

The usefulness of the circular table is enhanced if it is provided with a graduated scale; it can then be used to enable two vertical faces to be milled at any required angle, the one with the other. One face having been milled, the table is unlocked and turned through the appropriate angle as indicated on the scale; after re-locking the table the second face is then milled. In precision circular tables the scale is engraved on glass and read through a microscope as in the optical dividing head.

Continuous Milling. By using a large circular table provided with a number of work-carrying fixtures round its edge and by arranging this table on the work table of a vertical milling machine so that the fixtures pass under the cutter the milling can be made continuous. The operator then merely has to take the machined pieces out of the fixtures as they emerge from under the cutter and to put in unmachined pieces. The cutter must be sufficiently large to straddle the work. Machines are built in which such a circular table takes the place of the usual work table.

Profile Milling. When large batches of work having an irregular outline have to be milled special profile milling machines are used. These are made in various forms but they all work on the same basic principle, which is indicated in Fig. 242. The work is secured to a work table which can be traversed in the direction XY on the bed ways of the machine and the cutter, an ordinary end milling cutter, is carried in a head that can be traversed in the direction ST at right angles to XY. Fixed to, or made integral with, the cutter head is a bracket that carries a follower roller A which engages a *former* or *copy* fixed to the work

table. The traverse motions of the work table and cutter head are manipulated so as to make the follower roller travel round the former, with the result that the cutter reproduces the shape of the former on the work. If the cutter is the same in diameter as the follower roller then the former will be made an exact duplicate of the shape required on the work; otherwise, the difference in the diameters must be allowed for in the shape given to the former. The bracket that carries the follower roller is usually separate from the cutter head and the two parts are connected by an adjustable coupling; this allows greater latitude in the setting of the work. The cutter head and follower bracket can be independently adjusted vertically. By disengaging the screw and nut traverse mechanism of the work table and arranging a spring, a compressed air or hydraulic cylinder or a dead-weight which tends to move the table from Y to X, the operation of the machine when doing the portion *ab* of the profile may be reduced merely to giving the cutter-follower head a slow traverse motion from right to left. The portion *cd* can be done in a similar manner, the work table spring or dead-weight being arranged to urge the table from X to Y. For the portions *bc* and *da* the traverse mechanism of the cutter-follower head may be disengaged and a spring or dead-weight be arranged to urge that head to left or right, the work-table traverse being re-connected and used.

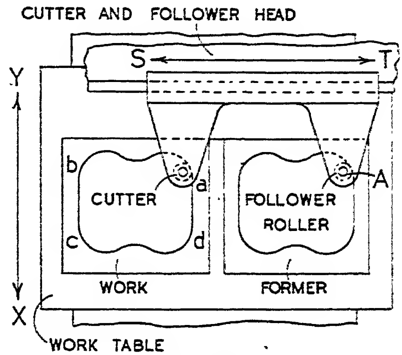


Fig. 242.

Other Forms of Milling Machine. The larger vertical milling machines are not made with a knee but have the saddle sliding directly on the bed ways; the vertical adjustment of the cutter head is then made sufficient to allow for different heights of work. For very large work the *Plano type* milling machine is used; this may be regarded as a planing machine (see p. 244) in which cutter heads provided with spindles to carry milling cutters take the place of the tool heads and in which the table motion is a slow-speed motion as required for the feed. Another type of machine that has been used extensively in quantity production is the drum type milling machine. This consists essentially of two massive columns each carrying one or more horizontal spindle heads and of a multi-faced drum which is carried by a stiff shaft in bearings in the columns. The work is bolted to the faces of the drum which revolves continuously with a slow-feed motion; the work is thus caused to pass between the face cutters carried by the spindles and its end faces are

both machined simultaneously. The work is put on and removed without stopping the drum.

"Climb-cut" Milling. This is a milling process in which the direction in which the work is fed relative to the cutter is just the opposite of that normally used, being as indicated in Fig. 243 instead of as shown in Fig. 219. The rotation of the cutter tends to drag the work underneath the spindle, and in a machine with ordinary feed arrangements this would lead to excessive chatter, broken cutters, and bent mandrels. When specially designed feed mechanisms are employed the method can be successfully used and is claimed to have advantages over ordinary milling.

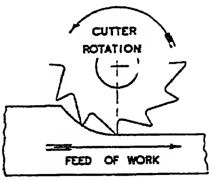


FIG. 243.

Cutting Speeds and Feeds. These are dependent upon similar factors to those that determine the life of a lathe tool but these factors have not, so far as milling cutters are concerned, been made the subject of any considerable experimental work and the selection of speeds and feeds is even more of an art and less of a science than with lathe tools. As a general guide the values given in the table below may be used, but it should be realised that such factors as the rigidity of the work itself and the power available to drive the machine must frequently be taken into account.

Material	*Cutting speeds, ft. per min.* *Roughing*	*Finishing*	*Feeds* *In. per rev. of cutter*
Cast iron	50–80	80–100	0·050–0·350
Mild steel	65–70	90–100	0·020–0·050
Carbon steels	40–65	60–90	0·020–0·050
Cast steel	30–60	50–80	0·010–0·030
H.S. steel	40–50	60–75	0·010–0·030
Brass, rolled	200–300	250–350	0·010–0·040
Brass, cast	100–200	150–250	0·010–0·030
Aluminium, Elektron	Maximum of machine		0·005–0·025

The above values are for high-speed steel cutters, for cemented-carbide tipped cutters they may be multiplied by 3–6. Feeds should not be very fine even for finishing cuts and may range from as low as 0·005 in. per revolution with aluminium up to 0·350 in. per revolution with cast iron. The feed per revolution depends to some extent on the number of teeth in the cutter. The power required by milling cutters varies considerably, but the following figures will give some idea of the magnitudes :

70 ton steel	0·4	cu. in. per horse-power per minute
Mild steel	0·9	,, ,, ,,
Cast iron	1·25	,, ,, ,,
Brass, rolled	1·9	,, ,, ,,
Aluminium	3·0	,, ,, ,,

Thread Milling. This is a method of machining screw threads which is alternative to the use of a single-point tool, a die-head, or a tap. There are two distinct types of thread milling process, one of which is used for long external threads, usually of acme thread form, such as lead-screws for machines, and the other for the short, Vee-form, external, or internal threads used to enable one piece to be secured to another. The first type of machine somewhat resembles a lathe in which the saddle is replaced by a cutter head. The cutter, which is usually situated at the rear of the work, is a form cutter and the spindle head that carries it can be swivelled about a horizontal axis perpendicular to that of the work, so that the plane of the cutter can be made tangential to the helix of the thread being cut. The motion of the cutter head saddle is controlled by a lead-screw which is geared to the headstock spindle and thus to the work. The speed of rotation of the work is, of course, quite low since this motion provides the feed and determines the thickness of the chips removed by the cutter teeth. The work spindle is usually provided with an indexing device to facilitate the machining of multi-start threads. The axial motion is sometimes given to the work table and work instead of to the cutter head, the only motion of the latter being then its transverse motion to adjust the depth of cut.

The second type of thread milling machine uses a multi-ribbed cutter which is usually as long as, or longer than, the thread being milled. The cutter resembles a hob (see p. 261) except that its ribs are not helical. The cutter is usually fed in or out radially towards the work, the work is rotated slowly, and either the cutter or the work is moved axially in synchronism with the rotation of the work. Generally the work rotates only a little more than one revolution and the axial motion is therefore only little more than one pitch. This type of thread milling is eminently suitable for threads running up close to a shoulder and for internal threads generally. The cutter axis is usually parallel to the work axis, no tilting being found necessary to accommodate the helix angle of the thread being cut.

Chapter 16

PLANING, SHAPING, AND SLOTTING MACHINES

An example of a large modern planing machine is shown in Fig. 244. The work table A slides on ways on the bed B which rests on massive foundations. A special form of electric drive is employed to reciprocate the table; the cutting stroke, which is from left to right as the machine appears in the illustration, can be at any mean speed ranging from 20 up to 200 ft. per minute. The return stroke is performed at a speed of 110–220 ft. per minute. The reversal of the motion at each end of the

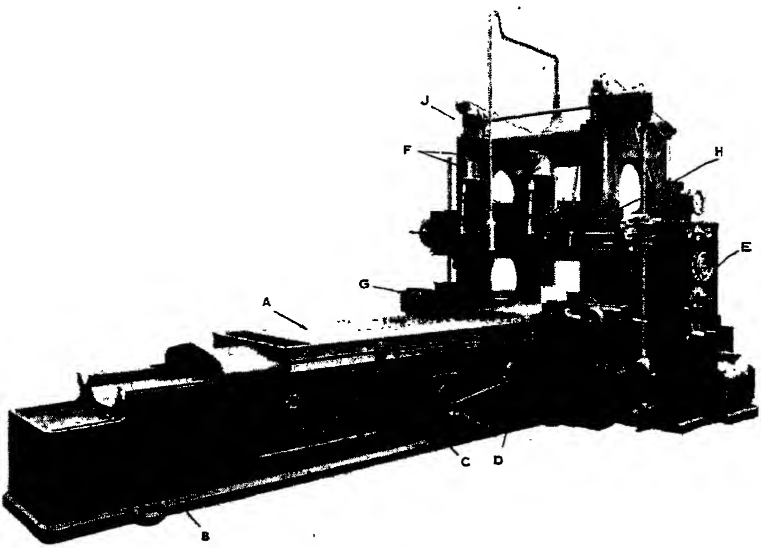


Fig. 244.

stroke is controlled by dogs C and D which can be clamped at any points along the edge of the table. The dogs operate electrical contacts which in turn control the main electrical contactors in the control panel E. The length of stroke is thus determined by the setting of the dogs C and D. The table can also be started, in either direction, and stopped, by means of a push-button control. An " inching " motion is provided by means of which the table can be moved in short steps, if required. The special form of electric drive keeps the accelerations and decelerations at the reversals within bounds and also makes the demand on the supply mains less fluctuating. The cutting tools are held in tool-heads F, F and G, G, the former being carried on the beam H and the latter on the faces of

the columns JJ up and down which the beam can slide. The beam is counterbalanced and, normally, is locked to the columns, being raised or lowered only to accommodate work of different heights. The tool holders are carried in slides in the tool-heads and these slides can be swivelled so that the tool motion can be at any angle from 0 degrees to about 60 degrees to the vertical. This enables inclined surfaces, such as the V-ways of a machine tool bed, to be machined, the tool holder being fed along its slide in the tool-head which is stationary on the beam. When machining a horizontal surface the tool-heads are fed across the beam and the tool holder slide is used to adjust the cut. The tool heads G, G are carried direct on the faces of the columns and the tools they carry work on the sides of the job. These side tool-heads can also be swivelled. The feed motion of the tool holder along its slide in the tool-head, or of the tool-head across the beam, or up or down the column, is given intermittently at the end of the return stroke of the table. The feed motion, in conjunction with the motion of the table, generates the required surfaces on the work.

The tools used are similar in general appearance to lathe tools and the cutting and clearance angles are usually about the same in both types. Planer tools, however, are frequently made goose-necked, as shown in Fig. 245, in order to reduce the tendency of the tool to " dig-in." When the tool springs under the force of the cut the overhung portion turns approximately about the point 0 and if the cutting edge were in front of the line OP this would cause it to dig in as indicated. If, however, the cutting edge is behind OP, then the spring of the tool will move it away from the work and digging in will be avoided. If very stiff tools are used they need not be goose-necked.

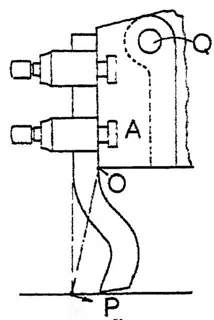


FIG. 245.

To avoid rubbing of the tool on the surface of the work during the return stroke the tool is carried in a *clapper box* (A, Fig. 245) which is pivoted to the tool slide on a pin at Q ; on the return stroke the clapper box pivots slightly and this enables the tool to ride quite lightly over the work. In the absence of the clapper box the rubbing would soon ruin the edge of the tool. In large machines the clapper boxes are actuated positively so that the tool is lifted clear of the work on the return stroke.

The clapper-box assembly can itself be swivelled relatively to the tool-holder slide, as is indicated in Fig. 246. The tool-holder slide is shown swivelled round so that its motion is in the direction XX. The clapper-box assembly A has been swivelled on the tool-holder slide so that the axis YY of the clapper-box point pin is at a slightly greater angle to the horizontal than XX is to the vertical. The clapper box thus swings in the plane ZZ perpendicular to YY and the corner of the tool, swinging in a parallel plane, will clear the machined surface of the work. This point

must always be considered when machining surfaces that are not horizontal.

The work is held on the table usually by means of holding-down plates and bolts, but special fixtures may be used and it is common practice to place a number of pieces of work end to end on the work table so that they can all be machined at once. Special attention must be paid to the endwise locating of work since the forces acting during reversal and when the tool commences to cut may be quite large. As in milling practice, frail parts must be adequately supported by packings or jacks.

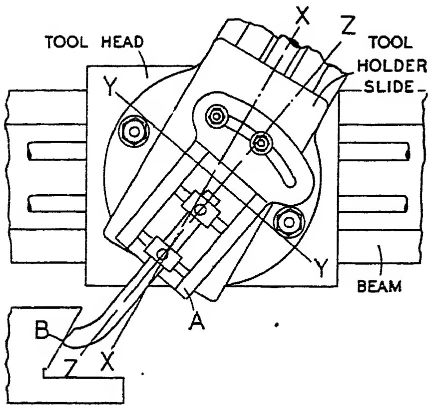


FIG. 246.

The setting up of the work on the table may take almost as long as the actual machining, and in order to reduce the time during which machines are idle it is common practice to use two subsidiary tables in connection with each planing machine. The work is set up on the subsidiary table alongside the machine while the work previously set up on the other table is being planed on the machine. When the machining is finished, the one table is lifted off and the other lifted on by means of an overhead crane. This reduces the idle time of the machine to that required to change over the subsidiary tables.

The Shaping Machine. The commonest form of shaping machine is that shown in Fig. 247. It consists of a massive body casting whose face is machined to take the saddle A and whose top surface provides ways for the ram B to slide along. The ram is driven to and fro by a mechanical linkage housed inside the body and the length of stroke can be adjusted to any amount within the capacity of the machine. The position of the stroke motion relative to the work can be adjusted by unlocking the clamp D that couples the ram to the driving linkage, moving the ram in or out as required, and re-clamping. The driving linkage automatically provides a quick-return motion.[1] The work table C can slide across the face of the saddle A and the latter can slide up and down the face of the body, both motions being by means of a screw and nut. The saddle is moved up or down to accommodate work of different heights but is locked during cutting. The cut is usually adjusted by moving the tool holder E in its slide F and the latter can be swivelled

[1] See the author's "Mechanism and the Kinematics of Machines," p. 122.

round on the end of the ram; this enables inclined surfaces to be machined by feeding the tool holder along its slide. A clapper box is provided and the tools used are similar to those used in planing machines. It will be seen that in shaping and in planing machines the motions of the tool relative to the work are identical although the actual motions,

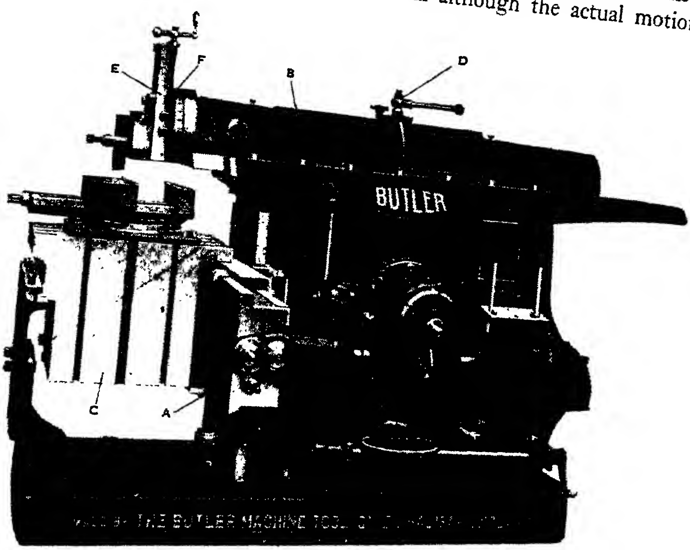


FIG. 247.

relative to the frame, are quite different, the cutting motion being obtained by moving the tool in the shaper and the work in the planer and the feed motion being given to the work in the shaper and the tool in the planer. The work is very commonly held in a vice in shaping machines but may also be bolted to the top or side of the work table.

The Slotting Machine. This machine, as will be seen from Fig. 248, also has a reciprocating ram B, which carries the tool, but the motion is now in a vertical direction although the ram slide can be adjusted so that the motion is in a direction making an angle of up to 5 degrees with the vertical. The ram is driven by a mechanical linkage and the upward, or return, motion is performed at a higher speed than the downward cutting stroke. The length and position of the stroke are adjustable as in the shaping machine. The machine shown has a circular table D built as an integral part but sometimes the circular table, which is of great use with slotters, is an accessory and is bolted on to the work table when required. The table D revolves on a cross-slide E which is able to traverse left or right, as seen from the front of the machine, on the saddle

A. The latter can traverse forwards or backwards on the bed ways. The feed motion is given to the saddle, cross-slide, or circular table

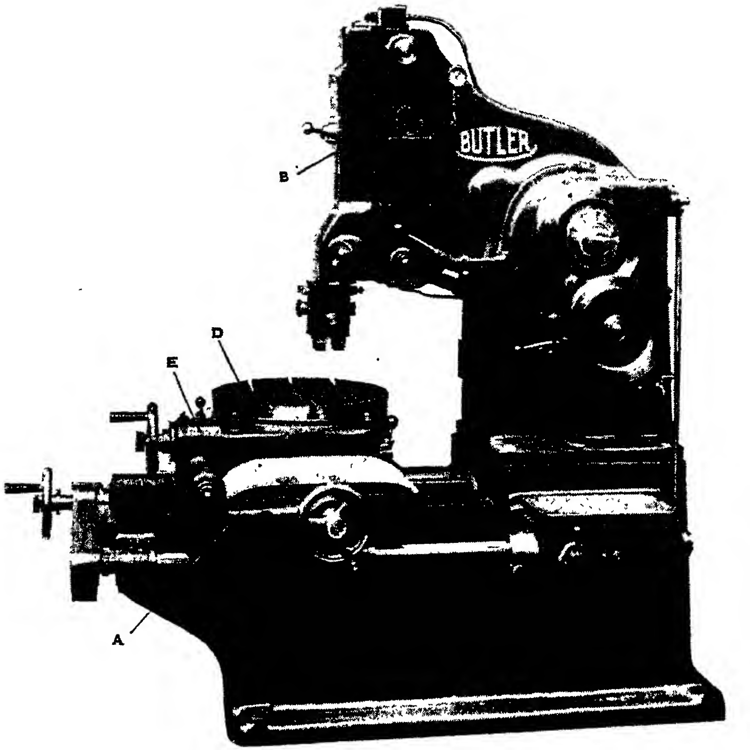


FIG. 248

intermittently as in the planer and shaper. Tools similar to those used in shaping machines are sometimes used and are then held on the bottom face of the tool holder as shown in Fig. 249. The work has usually to be raised up on packing pieces A in order to allow the cutting edge of the tool to over-run the bottom of the work and to prevent the ram from fouling the work table. The tools most used, however, are special to the slotting machine and are held on the vertical face of the tool holder as shown in Fig. 250. Such tools can be used to work on the insides of recesses,

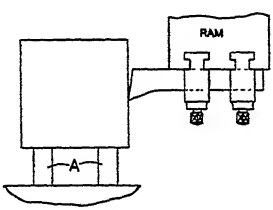


FIG. 249.

a type of job for which the slotter is particularly suitable. Tools made of small section ($\frac{3}{8}$–$\frac{3}{4}$ in. square) tool steel and held in a bar clamped

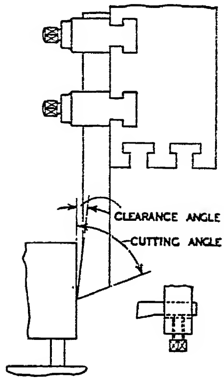


FIG. 250.

to the face of the tool holder (see inset sketch) are also commonly used.

The Special Field of the Planer, Shaper, and Slotter. The importance of these machines in engineering workshops has been greatly diminished since the development of the milling machine but for certain types of operation they still remain the best, while for some operations the slotting machine is the only suitable machine. Holes having sharp corners cannot be milled but can usually be done easily in a slotting

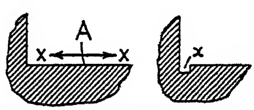


FIG. 251.

machine, although, if they are to be done in large quantities, they might sometimes be broached, as described in the next chapter. A tapered hole or one having surfaces inclined to the axis cannot, however, be broached but can be done on a slotter having a tilting ram slide. Certain recessed surfaces, such as the T-slots in machine tool work tables and the V-ways of machined slides, can be milled only with end mills and planing and shaping machines can generally do such jobs in shorter time. It should, however, be noted that planing, shaping, and slotting tools cannot cut right up to a dead end so that a surface such as that at A in Fig. 251 could not be shaped, at least by a tool moving in the direction XX. If a " landing groove " *x* can be arranged, the operation becomes possible.

Chapter 17

THE BROACHING PROCESS

Broaching is a process that has developed from being an operation carried out by fitters for occasional jobs to a machine shop process which increases in importance every day and which has already replaced other machining methods for many jobs. The principle of the process will be easily understood by considering Fig. 252 which shows a very simple

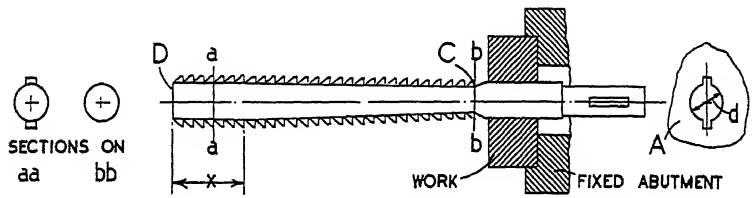


FIG. 252.

broaching operation. It is desired to produce a hole having two keyways as shown in the enlarged view at A. The hole is first bored to the diameter d and then the broach is pulled through it. At the end C the cross-section of the broach is in a circle, diameter d; at the other end D the cross-section is that of the required hole. The shape of the cross-section gradually changes from that at C to that at D except that a short length X is parallel and all has the finished cross-section. The broach is formed with teeth as indicated and as it is pulled through the work each tooth takes off a chip, with the result that the shape of the hole gradually changes from the circular to the required shape. The speed at which the broach is pulled depends on several factors such as the material of the job and the shape of the hole, etc.; it is not very high, ranging from as low as 5 ft. up to as high as 40 ft. per minute. The teeth

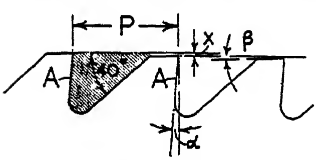


FIG. 253.

of the broach are somewhat like those of milling cutters and an enlarged view is given in Fig. 253. The land of the tooth is ground to give a clearance angle β which is usually about 1 degree on the cutting teeth and 2 degrees on the sizing teeth, and the faces A are inclined at an angle α which varies from 0 degrees to 15 degrees according to the material being broached. The pitch P of the teeth ranges from $0{\cdot}3\sqrt{L}$ to $0{\cdot}5\sqrt{L}$ in. where L is the length of the hole being broached and, in conjunction with the number of teeth, this determines the length of the broach, which ranges from as little as 1 ft. up to as much as 5 ft.,

the maximum length being determined by maximum stroke of the machine in which the broach is to be used. The amount x by which each successive tooth is " proud " of the preceding one determines the thickness of the chip removed by the tooth and the space between the teeth, shown stippled, must be large enough to house the chip. The thickness of chip that is practicable is determined to a large extent by the load exerted on the broach and its cross-sectional area ; that load in turn depends on the material of the work, the perimeter of the tooth, and the number of teeth of the broach that are simultaneously engaged with the work, a factor that is determined by the axial length of the work and the pitch P of the broach teeth. The chip thickness x ranges, in practice, from 0·0003 to 0·020 in. A representative batch of broaches is shown in Fig. 254.

The machines in which the broaching is done may be divided into orizontal machines and vertical machines according to the position of

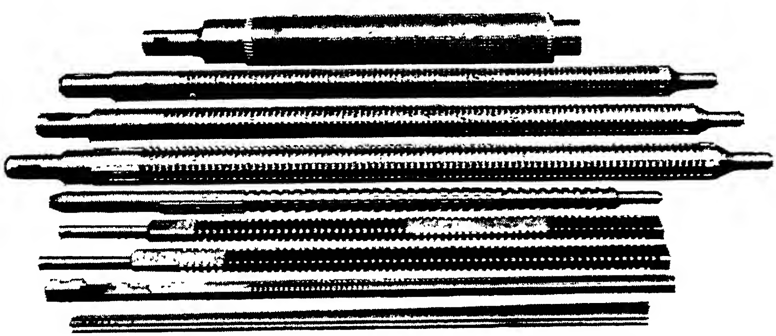


Fig. 254.

the broach when working ; the horizontal machine is, however, rapidly being displaced by the vertical machine which occupies much less floor space and which obviates any trouble due to sagging of the broach under its own weight. Vertical machines are almost invariably hydraulic in operation although they are made self-contained by building the hydraulic pump, that supplies the necessary pressure fluid, into the machine. The horizontal machines were frequently mechanically operated by means of a screw and nut. Fig. 255 shows a typical modern broaching machine.

The broach shown in Fig. 252 is an internal one and operates on the inside of a hole in the work, but external broaches are coming more and more into use ; they are considered later. For internal broaching operations the work is not usually rigidly held in the machine, it is generally held in a simple fixture by the pressure of the cut and is sometimes allowed radial freedom so that it can align itself with the broach. The cut, in the example given, is a balanced one, the chip removed at

one side being balanced by that at the opposite side. Unbalanced cuts sometimes cause difficulties.

Broaches are made usually of high speed steel and their first cost may be quite high, up to two or three hundred pounds for example. Long broaches also are liable to warp during the hardening and tempering process and may have to be scrapped for that reason. It follows that a broach cannot economically be employed for small quantities of a job.

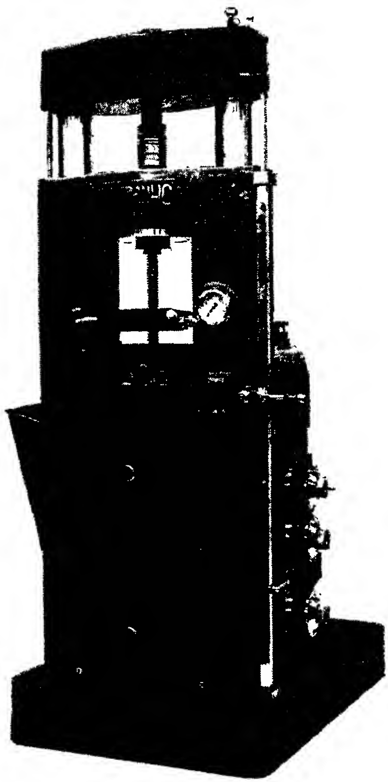


FIG. 255.

The life of a broach is, however, usually very long and may amount to as many as 200,000 pieces and so for parts which are required in large numbers broaching is generally the cheapest process. The accuracy and surface finish obtained by broaching are also very high; it is comparatively easy to maintain dimensions to plus or minus 0·0001 and broaching is consequently sometimes employed for circular holes which could be bored or reamed.

External or Surface Broaching. The principle underlying external broaching is the same as in internal broaching; the broach A, Fig. 256, is dragged past the work B which is firmly clamped on the work table C. Clearly the cut is quite unbalanced and the broach must consequently be adequately supported against the force of the cut which tends to move it away from the work; it is therefore carried in a holder which is provided with long bearing surfaces where it slides in the frame of the machine. The work-holding fixture and work table must also be rigid enough to withstand the reaction of the cutting force without appreciable spring. The teeth of external broaches are sometimes perpendicular, but are sometimes inclined at a smaller angle than 90 degrees, to the length of the broach. External broaches of complicated cross-section are frequently built up of several sections since this greatly simplifies their manufacture. External broaches are also commonly divided into sections lengthwise, partly because this also simplifies the manufacture and partly because it obviates the scrapping of the whole broach if a tooth is damaged or if some teeth have to be re-ground more frequently than others.

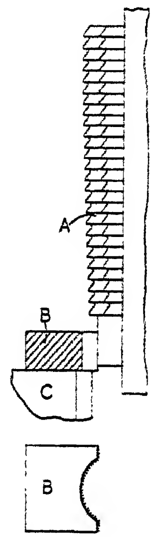


FIG. 256.

The machines used for external broaching vary considerably in design, those intended for general purposes on a range of jobs are usually vertical. Many machines designed for a particular job, such as the top surfaces of a V cylinder block, are horizontal however, and in these special machines it is sometimes the broach that moves and sometimes the work table and work. In one machine the work is placed in fixtures carried by an endless chain and is thereby dragged between a fixed abutment and the fixed broach.

The principal reasons for the greater accuracy and better surface finish of work that is broached as compared with work that is finished by other processes are first, that the broach teeth that take the finishing cut never take any roughing cuts and, secondly, that there is only one moving part in the broaching machine which directly affects the accuracy of the work, namely, the slide that carries the broach. The facility with which accuracy and finish are maintained over long periods, and the low cost per piece when large quantities are dealt with has already caused external broaching to displace milling on many jobs despite the comparatively recent development of the process.

Chapter 18

GEAR CUTTING

The subject of gear cutting is a very wide one and space is available in this book to deal only with the general aspects of it. In order to understand the action of gear-cutting machines it is necessary to have some knowledge of the principles underlying the action of gear teeth, but this is beyond the scope of this book and it will be assumed that the reader possesses that knowledge. The principles are dealt with at length in the author's book " Mechanism and the Kinematics of Machines."

Toothed gears may be classified thus :

1. Spur gears : (*a*) Straight toothed ;
   (*b*) Helical or double-helical toothed.
2. Bevel gears : (*a*) Straight toothed ;
   (*b*) " Spiral " toothed.
3. " Hypoid " gears.
4. Skew gears.
5. Worm gears : (*a*) Parallel type ;
   (*b*) Hindley or Globoid types.

and gear-cutting machines may be classified in the same way except that there are no Class 4 machines, skew gears being cut on the same machines as either helical-toothed spur gears or worm gears. Gear-cutting machines can also be divided into :

(*a*) Copying machines.
(*b*) Generating machines.

Machines will be considered in the order set out above and copying processes will in each case be considered before generating processes.

Spur Gears. The only copying process of any importance is the milling process using formed cutters whose shape corresponds to the shape of the space between the gear teeth. The cutting may be done in an ordinary milling machine using a dividing head to give the spacing of the teeth or in a specially designed machine. The profile of the tooth is a direct copy of that of the cutter and, since the shape of a gear tooth depends on the number of teeth in the gear, it would be necessary, if really accurate teeth were required, to have a different cutter for every different number of teeth. In practice this was never done because it would have involved too great a cost for cutters and a set of eight cutters was made to cover all numbers of teeth in the involute system, while a set of twenty-four was used for cycloidal teeth. The involute cutters were numbered 1–8 and were used as set out in the table below. Intermediate cutters increasing the set to sixteen in all can also be obtained.

Cutter number .	1	2	3	4	5	6	7	8
No. of teeth cut	∞–135	134–55	54–35	34–26	25–21	20–17	16–14	13 and 12
Cutter number .	$1\frac{1}{2}$	$2\frac{1}{2}$	$3\frac{1}{2}$	$4\frac{1}{2}$	$5\frac{1}{2}$	$6\frac{1}{2}$	$7\frac{1}{2}$	
No. of teeth cut	134–80	54–42	34–30	25–23	20–19	16–15	13	

The shape of each cutter is accurate for only the lowest number of teeth in its range and for the other numbers there is a discrepancy ; when this is not permissible a special cutter for the particular number of teeth to be cut can be obtained.

In using formed cutters it is very important that the central plane of the cutter should contain the axis of the gear being cut, but it is not easy to obtain that setting accurately. Some methods of doing this will now be described.

Setting the Cutter Central. One method is shown in Fig. 257*a*. The knee is raised so that the cutter can be brought into contact with the side of the wheel blank as shown by the full line circle,

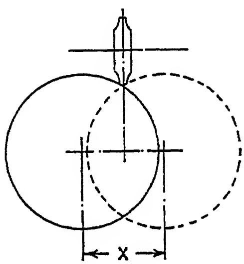


FIG. 257*a*.

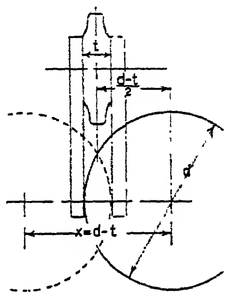


FIG. 257*b*.

the actual contact is obtained by feeding the saddle across until the rotating cutter just touches the work. The readings of the saddle traverse and knee elevating dials are noted and the knee is then unlocked and lowered so that the saddle can be traversed across a distance somewhat greater than x in the figure. The knee is raised to its former position and locked and then the saddle is traversed until the cutter makes contact as indicated by the dotted outline. The saddle dial is read again and the distance x is thus obtained. The saddle is then moved back a distance $x/2$ and the axis of the work will then be in the central plane of the cutter. The drawbacks to this method are, first, that the amount of contact of cutter and work is not definite to within a thousandth of an inch or so of saddle movement and, secondly, the backlash in the saddle traverse nut must be allowed for and this also cannot be established with an accuracy greater than about $\pm 0{\cdot}001$ in.

A second method is the same as the above in principle, but instead of bringing the cutter into contact with the work a straight edge held against

the cutter is made to contact the sides of a mandrel held in the dividing head, as indicated in Fig. 257*b*. The distance x is thus established from the saddle dial readings and the saddle is traversed back the amount $x/2$. In this method backlash can be obviated by moving the saddle too far on making the second contact and then moving it back again.

A third method uses a straight edge as in the second method, but makes contact on one side only of the work, the requisite saddle movement $\frac{d-t}{2}$, from the position of contact, being calculated from the measured dimensions d and t.

The principle of a method developed by the author is indicated in Fig. 258. A device consisting of a bracket A which can revolve on a base B is clamped to the machine table and the spindle of the dial indicator C is brought into contact with the cutter so as to give a reading. The knee is then lowered and the bracket A is rotated exactly 180 degrees. This is determined by means of a pin D which engages diametrically opposite holes E, E. The knee is raised to its former position and the saddle is traversed until the dial indicator reads the same as at first. The saddle movement x is obtained from the saddle traverse dial readings and the saddle is moved back half that amount. Backlash can be obviated as in the second method. It is important that the dial indicator spindle axis shall lie in the plane containing the axis OO and the diameter EE_1 and that the latter should be perpendicular to the work-table ways.

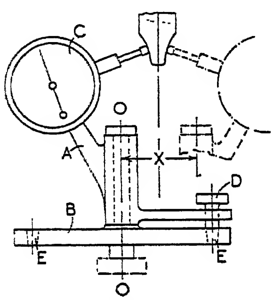


FIG. 258.

Formed gear cutters generally have the depth to which they must be sunk into the blank engraved on them and a first approximation to the correct depth may be obtained by means of the knee elevating screw dial. For greater accuracy the depth is settled by measuring the tooth thickness of the gear or by taking a measurement across a pair of rollers placed in diametrically opposite tooth spaces. These and other gear measurements are considered in Chapter 19.

Theoretically if a formed cutter is not sunk to the correct depth the tooth action will be imperfect, but in practice the depth does not seem to be very critical except for gears having small numbers of teeth. This is particularly so when both gears of a mating pair have the same kind of error, and this enables the backlash to be adjusted by varying the depth to which the cutters are sunk. The *excess* depths beyond the standard amounts should be made proportional to the numbers of teeth in the wheels. To a first approximation the increase in the circumferential backlash due to an increase a in the depth to which a cutter is sunk beyond the standard amount is $a/2$.

Cutting Speeds for Formed Gear Cutters. These are generally low compared with those used in other operations because too high a speed involves the risk of serious damage to an expensive cutter and also may reduce the accuracy of the product. It is also advisable to avoid having to disturb the set-up of the cutter relatively to the work until the job is completed. Cutting speeds are consequently only about 50–80 per cent of those used with ordinary milling cutters.

Gear cutting by means of formed cutters is no longer used for large quantity production because the cost of production is too high and the accuracy obtainable is not high enough. For small quantity production it is the standard method and is widely used. When specially accurate cutters are used under favourable conditions the accuracy obtainable equals, and may exceed, that obtainable by any process except grinding with a formed grinding wheel.

The Rack-Cutter Generating Process. The underlying principle of this process is as follows. The blank, on which gear teeth are to be cut, is mounted on a mandrel which is geared to a slide carrying the cutter B (Fig. 259). The cutter is identical, except for certain small details, with the rack that would mesh properly with the gear-wheel after its teeth have been cut. The slide carrying the cutter B can move in the direction XY and is placed so that the distance L between the pitch line of the cutter teeth and the axis of the blank is the correct distance. The gearing between the cutter slide and mandrel is arranged so that when the mandrel is rotated the cutter slide moves along exactly as it would do if the pitch circle of the teeth being cut engaged, without slip, the pitch line of the rack cutter. If the blank were made of a perfectly plastic material then, as the rack passed under the blank its teeth would mould the blank into a wheel with teeth correctly shaped to mesh with the rack and consequently, provided certain conditions as regards the shape of the rack tooth are fulfilled, with any other wheel formed by the rack. Since the blank is not plastic the rack has to be made to cut it. The rack edges are made cutting edges and it is given a reciprocating motion in a direction perpendicular to the plane of the paper in the sketch; that is, parallel to the axis of the blank. This reciprocation is at a fairly high speed whereas the generating motion, that is, the rotation of the blank and sliding of the cutter in the direction XX, is comparatively slow and is given intermittently during the return stroke of the cutter. The

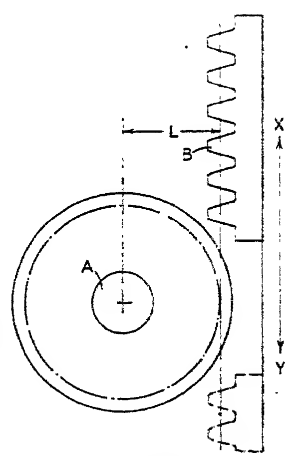


FIG. 259.

generating action will be evident from a consideration of Figs. 260 and 261 in the former of which, in order to simplify the drawing, the blank has been kept fixed and the rack rolled round it just as if the rack

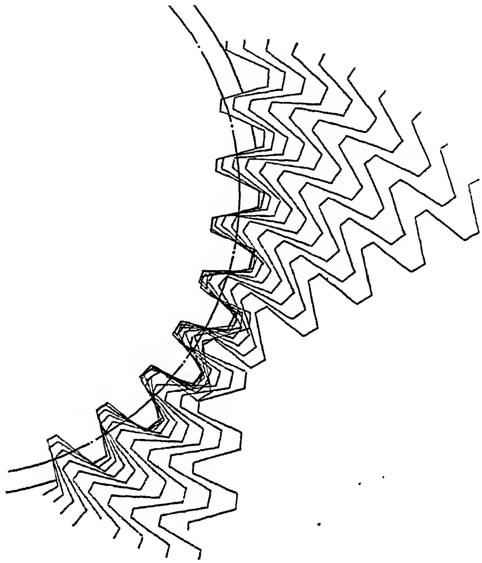


FIG. 260.

pitch line rolled without slip round the blank pitch circle; the relative motion between rack and blank is exactly the same as when the blank rotates and the rack merely slides.

The great advantage of the above principle is that in the involute system of gear teeth, which is the system almost exclusively used, the rack teeth are straight-sided and can be made with greater accuracy than any formed cutter. The system is also much more flexible as non-standard teeth can frequently be cut perfectly accurately with standard cutters simply by varying the distance L between the rack cutter and blank axis. Again, only one cutter is required for all wheels of the same pitch, regardless of the number of teeth.

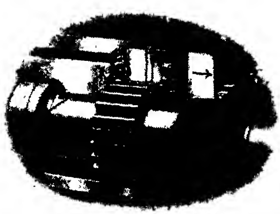


FIG. 261.

Machines embodying the rack-cutter principle were first developed by J. Parkinson & Son of Shipley, Yorkshire, and one of their latest machines is shown in Fig. 262. Because it is impracticable to use a rack cutter that is long enough to form all the teeth of a large wheel the cutters are made long enough to form only one or two teeth and a "step-back"

motion is used. In the generating motion the saddle C slides down the vertical face of the head D and when this motion has formed a tooth the head D is moved back along the bed E so that the cutter A is clear of the

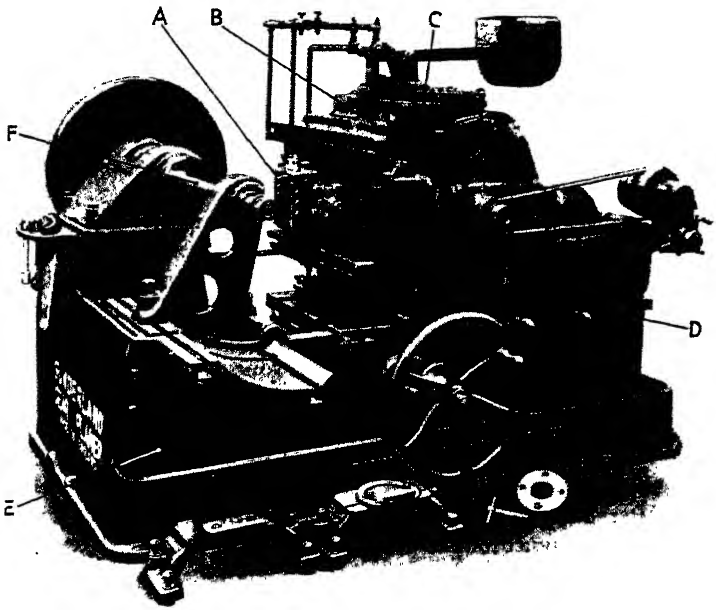


FIG. 262.

work, the gearing between the blank mandrel F and the saddle C is disconnected, and the saddle is raised to its initial position. The gearing between the cutter saddle and mandrel is re-connected and the next tooth of the blank is generated. The amount of the " step-back " motion must, of course, be an exact number of pitches. All the operations are performed automatically.

The cutter is carried in a positively operated clapper box and the cutter slide B can be swivelled on the saddle C so that the line of stroke of the cutter can be at any angle with the blank axis from 0 to 60 degrees. For cutting spur gears that angle will be 0 degrees. The ability to swivel the slide to other angles enables helical toothed gears to be cut as indicated in Fig. 263.

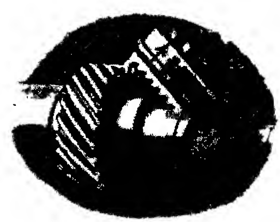


FIG. 263.

In the *Maag* machines, which also employ rack cutters, the blank axis is vertical, the machine being arranged rather like a slotting machine. The generating motion is given entirely to the blank, which is rolled past

the cutter, that is, it rotates about its axis while that axis is translated parallel to the cutter pitch line. A step-back motion is given to the blank after each tooth has been formed.

One of the advantages of the rack-cutter process, namely, the ease with which the cutter can be made accurately, is sometimes lost, to some extent, because an unsuitable design of tooth is used ; the defect is usually that too small a pressure angle is used in relation to the number of teeth in the smallest wheel to be cut. This results in the occurrence of " interference " and necessitates a modification of the rack cutter tooth ; the fault lies in the design of the teeth and not in the cutting process.

The Pinion-Cutter Process. This is fundamentally the same as the rack-cutter process but a pinion cutter is used instead of a rack cutter. The pinion cutter is given a reciprocating cutting motion parallel to its axis and the tooth generation is obtained by rotating the cutter and blank just as they would rotate if their pitch circles rolled together without slip. Since the pinion cutter can make as many revolutions as may be necessary there is no need for any " step-back " motion. At the commencement of the cutting the cutter is clear of the blank ; it is then fed in radially until the distance between the cutter and blank axes is the correct centre distance corresponding to the size of the gear being cut and of the pinion cutter. After being fed in to depth radially the cutter, and blank, are rotated slowly in synchronism until all the teeth have been cut on the blank.

Most machines using pinion cutters are arranged with the blank and cutter axes vertical, the generating motion is given intermittently on the return stroke of the cutter, which may be either the upward or the downward stroke, and the cutter is relieved on the return stroke usually by moving the table carrying the blank spindle away from the cutter.

The use of pinion cutters has two advantages and one disadvantage as compared with the use of a rack cutter. The advantages are that the machines are somewhat simpler because no step-back motion is required and that gears with internal teeth can be cut ; the disadvantage is that the pinion cutter is more difficult to make than the rack cutter. Pinion cutters are standardised in two sizes of pitch circle, 3 in. and 4 in. in diameter, the former being the one mostly used. The teeth are relieved so that their profile does not change on sharpening ; the tooth thickness, however, does change and this may sometimes have to be taken into account. Sharpening is done by grinding the face A, Fig. 264, which is a conical surface ; the angle θ is usually 85 degrees.

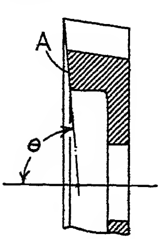


FIG. 264.

Non-standard teeth can be cut with pinion cutters by varying the centre distance just as they can be with rack cutters.

The Hobbing Process. A hob is really nothing more than a screw which has been gashed so as to give it cutting edges and which has been relieved like a formed milling cutter. If a screw is rotated about its axis, say XX in Fig. 265, for one complete revolution, the tooth outline ABCD will appear to travel to the right and will come to occupy the position EFGH. If the tooth outline is made the same as that of the rack in the rack-cutter process then the mere rotation of the hob will give the equivalent of a rack which moves continuously parallel to the axis of the hob and this equivalent rack can be used to generate the teeth of wheels. The rotation of the hob, in conjunction with the gashing that provides cutting edges, also provides the cutting action. The hob is mounted on a spindle whose axis is placed so that the pitch line PQ (Fig. 265*b*) of the "rack" teeth is tangent to the pitch circle of the blank. The hob spindle is geared to the blank mandrel so that when the hob is rotated and the "rack" traverses along PQ the blank rotates just as it

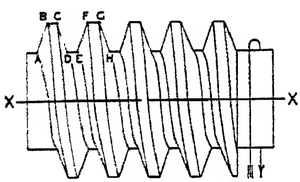


FIG. 265*a*.

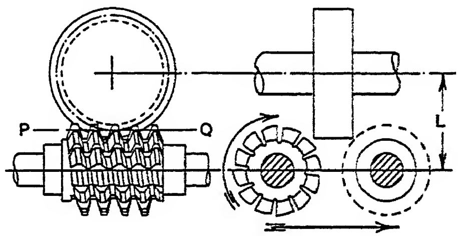


FIG. 265*b*.

would do if its pitch circle engaged the pitch line of the rack without slip. The gear ratio is easily established.

Let N = number of teeth in the wheel being cut.
n = number of starts in the hob.
s = r.p.m. of hob.
S = r.p.m. of blank.

Then $S \times N = s \times n$

and $\frac{S}{s} = \frac{n}{N}$.

Initially the hob is to one side of the blank as shown in full line in the end view (Fig. 265*b*), and it is fed slowly parallel to the axis of the blank until it reaches the position shown in dotted outline by which time all the teeth of the blank will have been correctly formed.

Some typical hobs are shown in Fig. 266; they are usually ground all over after heat treatment so as to obviate any errors due to distortion during hardening.

In the description given above it has been implied, more or less, that the axis of the hob is perpendicular to that of the blank but actually, because the hob teeth are disposed along a helix, the hob spindle is

inclined at the helix angle of the hob thread so that the tangent to that thread is parallel to the blank axis, as indicated in Fig. 267. Because of this tilting of the hob axis the shape of the rack teeth of the hob has to be modified somewhat. It is possible, however, to design a hob that will generate correctly shaped teeth for any value of the angle θ that may be selected. It is also possible to vary the tooth thickness of the blank by

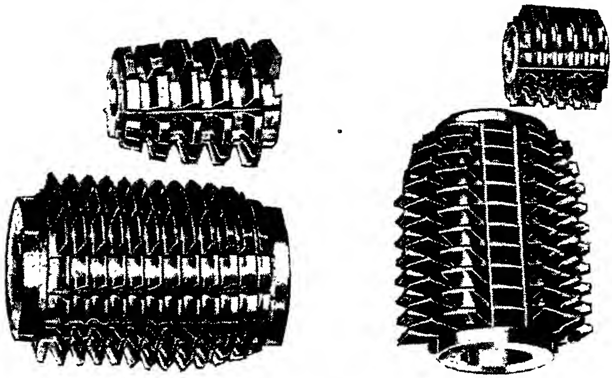


Fig. 266.

varying the angle θ with a given hob. For a detailed consideration of these problems the reader is referred to Earle Buckingham's book, "Spur Gears."

The speed of rotation of a hob is selected to give a suitable cutting speed for the material being cut and the speed of the blank is then settled by the number of teeth in the wheel being cut and the number of starts in the hob; the latter is usually unity but is sometimes two. As an example the hob speed might be, say, 80 r.p.m. and the blank speed 2 r.p.m. In the rack and pinion cutter processes the mean speed of the blank is very low, being of the order of $\frac{1}{10}$ r.p.m. because it provides the feed motion and determines the size of the cuts taken. In hobbing, the feed is due to the motion of the hob parallel to the blank axis and is comparable with those used in ordinary milling operations.

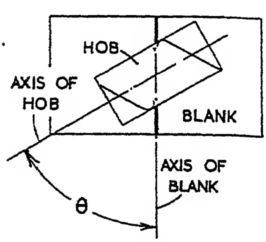


Fig. 267.

The hobbing process has the advantage that the motions of the hob and work are continuous, the heating of the work due to the cutting is also distributed all round the circumference of the blank, and so is any inaccuracy due to the gradual blunting of the cutting teeth. Hobs are, however, difficult to make and are expensive; nor can they cut teeth up to a shoulder as the rack and pinion cutters can.

Helical Teeth. Single helical teeth may be cut by the formed cutter process in a universal milling machine. The work table must be swivelled round through the helix angle of the teeth being cut so that the plane of the cutter becomes tangent to the tooth helix. The cutter must be selected to suit the shape of the tooth space on a section normal to the tooth helix. It can be shown that if the actual number of teeth in the wheel being cut is N and the helix angle is α then the cutter should be that one suitable for a straight-toothed wheel having $\dfrac{N}{[\cos \alpha]^3}$ teeth. A gear having this latter number of teeth is called the *equivalent spur gear.*

In the Sunderland machine helical teeth may be cut by swivelling the cutter slide, B in Fig. 262, through the helix angle of the teeth. The normal pitch of the gear will then be equal to the pitch of the cutter teeth and, if the same cutters that are used for spur gears are to be used,

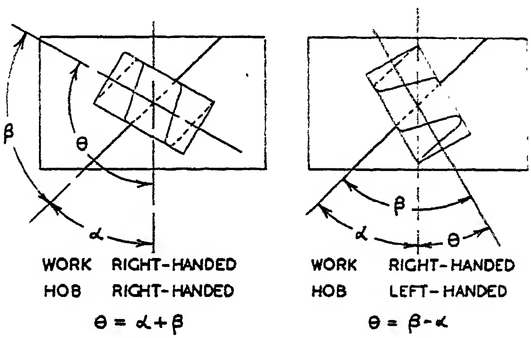


FIG. 268.

this must be a standard pitch. Special cutters with inclined teeth, similar to the cutters used to cut double helical teeth, may be used. In pinion cutter machines helical teeth can be cut only with special cutters and machines. The helical tooth form is obtained by giving the cutter an oscillatory rotation as it reciprocates up and down. This oscillatory rotation is independent of, and is superimposed upon, the slow continuous rotation of the cutter that provides the generating motion, and it is obtained by means of a helical guide fixed to the ram that carries the pinion cutter and which engages a similar guide carried in the cutter head. The helix angle of the tooth cut is thus the same as that of the cutter ram guide, and as it is impracticable to have many different guides the helix angle of the gears that can be cut is limited to one of about three standard values. The teeth of the pinion cutter must also be helical and must have the corresponding helix angle. It should be clear that if the teeth being cut are right-handed those of the cutter must be left-handed. The pinion cutter process is consequently not nearly so

flexible, or so widely used, as either the rack cutter or hobbing processes for helical teeth.

In the hobbing process helical teeth can be cut almost as easily as straight teeth. The hob has to be swung round so that the tangent to the hob tooth helix coincides with the tangent to the helix being cut but, as with straight teeth, this depends on the design of the hob. If the helix angles of the hob and work are respectively β and α and the angle between the hob and work axes is θ then, for most hobs, $\theta=\alpha+\beta$ or $\alpha-\beta$, according as to whether the hob and the work are of the same or are of opposite "hand." This should be clear from Fig. 268. If β is greater than α then, for opposite hands, $\theta=\beta-\alpha$.

The speed or rotation of the blank now depends not only on that of the hob but also on the rate of feed of the hob parallel to the axis of the blank and on the helix angle α of the tooth being cut.

Let N=number of teeth in wheel being cut.

n=number of starts in the hob.

s=r.p.m. of hob.

S=r.p.m. of wheel.

α=helix angle of tooth being cut.

A=feed of hob, parallel to work axis, in inches per minute.

a=feed of hob in inches per revolution of the hob.

P=real diametral pitch of teeth being cut.

D=pitch circle diameter of wheel in inches.

Then, if A were zero we should have $S_1=\frac{sn}{N}$ as before. If, however, s were zero, then the only rotation of the work would be due to the feed A of the hob and we should have

$$S_2=\frac{A\tan\alpha}{\pi D}=\frac{PA\tan\alpha}{\pi N}.$$

When the hob both rotates and feeds the speed of the blank will be the algebraic sum of S_1 and S_2. Hence we have

$$S=\frac{sn}{N}\pm\frac{A\tan\alpha}{\pi D}$$

$$=s\left[\frac{n}{N}\pm\frac{a\tan\alpha}{\pi D}\right]$$

since $$A=sa.$$

Hence, $$\frac{S}{s}=\frac{n}{N}\pm\frac{a\tan\alpha}{\pi D}$$

$$=\frac{n}{N}\pm\frac{Pa\tan\alpha}{\pi N}$$

since $$D=\frac{N}{P}.$$

The plus sign is used when the axial feed and the rotation of the hob both rotate the blank in the same direction and the minus sign if the rotations due to hob feed and rotation are opposite in direction.

Double Helical Teeth. In regard to cutting these, they may be divided into two types: those in which the right- and left-handed tooth portions are separated by a gap and those in which the two portions are joined together and form a continuous tooth. The former can be cut by any method suitable for single helical teeth provided the gap between the toothed portions is sufficient to provide clearance for the cutters; in general, hobbing will require a wider gap than cutting by other processes. The second type can be cut only on special forms of rack-cutter and pinion-cutter machines or by end milling. The rack-cutter machines employ two cutters, AB and A_1B_1 in Fig. 269, one for the left-hand toothed portion and one for the right-hand portion; these cutters are carried in slides which are inclined to the axis of the gear at the helix angle of the teeth and this angle is made a fixed quantity. The cutters reciprocate in synchronism, one cutting while the other is doing the return stroke, and they are made with their teeth parallel to the line of stroke as indicated in Fig. 269. The strokes of the cutter slides must be adjusted so that the cutting edges of the cutters come just flush with the centre line LM between the two tooth portions at the ends of the cutting strokes.

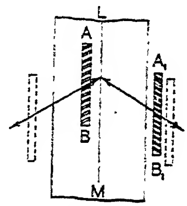


FIG. 269.

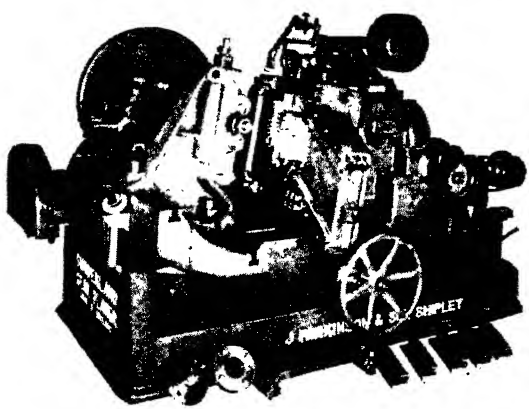


FIG. 270.

The tooth generation is obtained by sliding the head carrying the cutter slides in the direction LM and a step-back motion is used as when cutting straight teeth.

A Sunderland machine for cutting double helical teeth is shown in Fig. 270.

The pinion-cutter machine also employs two cutters. These are carried on spindles A and B, Fig. 271, in a common head C that reciprocates parallel to the axis of the blank. The spindles A and B are provided with helical guiding surfaces that engage corresponding surfaces in the frame of the machine so that as the cutters reciprocate they are also rotated and thus cut helical instead of straight teeth. The helix angle can thus be altered only by changing the guides. The cutter teeth must also be helical. The stroke of the head C, and the distance apart of the cutters, must be arranged so that the cutting edges just reach the centre line LM on the cutting strokes. The tooth generation is obtained by giving the cutters and the blank a slow continuous rotation; this motion is, of course, superimposed on the rotary oscillation of the cutters.

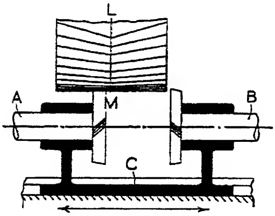


Fig. 271.

The End-Milling Process. This employs an end mill which rotates about an axis perpendicular to that of the blank and which is slowly traversed parallel to the axis of the blank. The profile of the cutter is made to the correct shape of the tooth space being cut and, by giving the blank a rotation in synchronism with the axial traverse of the cutter, the tooth can be made helical, or double or triple helical, as may be desired. The process is a very slow one and the accuracy attainable is not very high. The method is, consequently, practically obsolete, but it is the only method by which triple helical gears can be cut.

Gear Shaving. In recent years a method of finishing spur and helical gear teeth has been developed in which a very small amount of metal is removed by cutters which somewhat resemble broaches; this process has been called gear "shaving." If a straight-toothed gear wheel, A in Fig. 272, is rolled on a rack having inclined teeth the natural direction for the motion would be perpendicular to the axis XX and motion in that direction would not involve any sliding between the teeth of the wheel and rack in the direction XX. But if the gear is forced to roll in the direction YY, then sliding between the teeth in the direction of XX must occur; the motion from C to D, for example, is equivalent to a "pure roll" CE and a "pure slide" ED. Consequently, if the rack teeth are formed with cutting teeth on the lines of a broach, metal can be removed from the surfaces of the gear teeth. It is immaterial whether the axis of the gear remains stationary and the rack reciprocates beneath it or whether the rack is stationary and the gear moves bodily in the

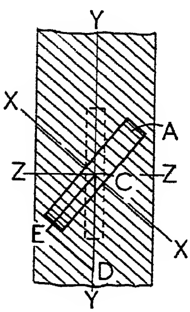


Fig. 272.

direction YY. Since a similar sliding motion, parallel to the gear teeth, occurs in skew gearing, the rack in Fig. 272 may be replaced by a second gear as indicated in dotted outline, having suitable cutting edges, rotating about a fixed axis ZZ. Machines are made on both principles and are much used by the automobile industry, particularly in the United States of America.

Bevel Gear Cutting Machines. These can also be classified as either copying or generating machines. The principle of the copying type of machine is illustrated in Fig. 273. The blank being cut, E, is mounted on a spindle F that is free to rotate in the bracket B and to which is fixed an arm D. That arm carries a former P which bears against a pin Q which is fixed to the frame of the machine. The bracket B is pivoted on that frame at C and the apex of the pitch cone of the gear E

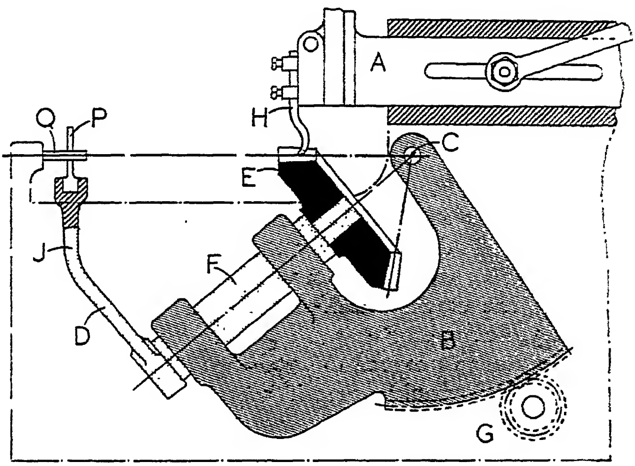


FIG. 273.

is made to coincide with the point C. The cutting tool H is carried in the ram A which reciprocates in a guide in the frame of the machine. A pinion G enables the bracket B to be moved upwards or downwards. A chain is attached to the arm D at a point J and passes over a pulley so that a weight on its end serves to keep the former P up against the pin Q. The cutting edge of the tool should have the same shape as the pin Q and its edge must be adjusted so that all its points lie on lines drawn from C to the corresponding points of the pin.

If the tool shape is different from that of the pin Q then the shape of the former P must be modified from that of the tooth required so as to allow for the difference.

The gear having been gashed with a parting tool which is fed in radially (by using a former P which is a straight line) the teeth are finished to

shape by substituting a side tool for the parting tool and a properly shaped former for the straight one. One side of a tooth is machined at a time and all the teeth are finished on one side before starting on the other sides. Each tooth side is done as follows. The bracket B is lowered until the blank is clear of the tool and the ram A is reciprocated. The bracket B is then slowly moved up until the tool reaches the bottom of the tooth space, the bracket is then lowered to its starting point, the blank is indexed round one tooth relative to the arm D, and the whole process is repeated. When the other sides of the teeth are to be done the former P must be changed round so as to bear on the opposite side of the pin Q. Clearly the outline of the tooth is a direct copy of that of the former.

A variation of the above arrangement is to keep the blank fixed and to move the slide carrying the cutter.

Copying machines of the types described above are still used to some extent but have been largely replaced by generating machines.

Bevel Gear Generating Machines. The underlying principle of these is similar to that of spur gear generating machines. In bevel gearing the *crown gear* is the equivalent of the spur gear rack. A crown gear is a bevel gear whose apex angle is 180 degrees and whose pitch surface is consequently a flat disc. The teeth of this crown wheel are made straight sided and the teeth of bevel wheels are generated by rolling the blanks with the crown wheel. The teeth thus obtained are known as *octoid* teeth. The crown wheel, with which the blank is rolled, is mostly imaginary, but one of its teeth is represented by a cutting tool and the machine has to produce the same relative motion between the tool and the blank as would occur if the crown wheel were actually present and the completed blank rolled on it. This relative motion may be obtained by keeping the tool fixed in space (except for the reciprocating motion which enables it to cut) and moving the blank, or by moving both blank and tool. A third possibility which, so far as the writer knows, has never been adopted, is to keep the blank fixed and give the whole of the motion to the tool. The first of these arrangements is illustrated in Fig. 274 which shows, diagrammatically, the main features of the *Bilgram* bevel gear generating machine. The blank B is fixed on a spindle C which is carried in a bracket M that is free to rotate about the vertical axis XA. Also fixed to the spindle C is a sector of a cone N whose apex lies at A, which is also the apex of the pitch cone of the blank. The cone N has the same apex angle as the pitch cone of the blank and its edge rests on a flat portion of a bracket Q, which is pivoted to the framework of the machine on a horizontal axis through A and which represents the pitch surface of the imaginary crown wheel which is going to roll with the blank B to generate teeth on the latter. Slip between N and Q is prevented by two steel tapes R and S. It follows that as the

bracket M is rotated about the axis XA the pitch cone N rolls without slip on the crown wheel pitch surface Q and the blank gets the same motion as it would do if its pitch surface rolled without slip on a flat disc representing a crown wheel pitch surface. The tool T is made with straight cutting edges to represent a tooth of the imaginary generating crown wheel and it receives a reciprocating motion along a line parallel to the line AZ. The blank is fed relatively to the tool by rotating the bracket Q, and this feed motion goes on until the line AY coincides with the line of stroke AZ of the tool point, and the tooth shape is then

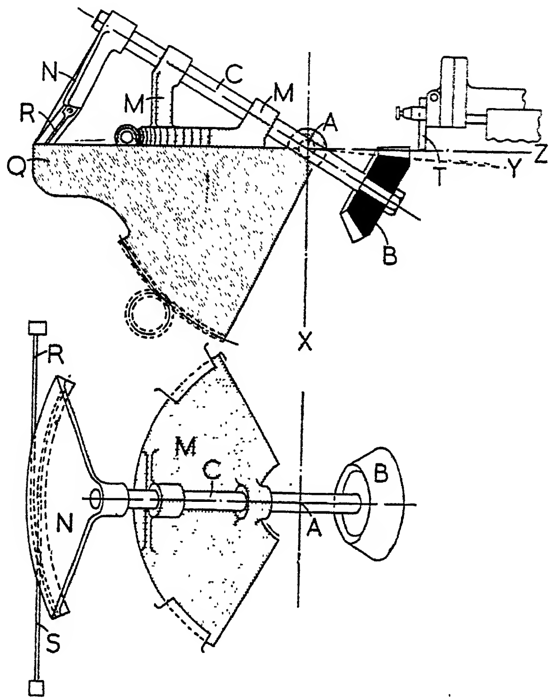


FIG. 274.

generated by the rolling motion of the blank due to the rotation of the bracket M. When one tooth space has been generated and the bracket Q has returned to its initial position the blank is indexed round one tooth relative to the cone N and the whole process is repeated.

The second arrangement, in which the relative motion between the blank and the imaginary generating crown wheel is obtained by moving both the tool and the blank, is used in the Gleason straight bevel gear generating machines. The machine is shown diagrammatically in Fig. 275. The blank B is fixed on a spindle C which can rotate about

the axis OAO in fixed bearings in the frame. Fixed to the spindle C is an arm N which carries a toothed sector P which represents an enlargement of the gear B being cut. The toothed sector P meshes with a second toothed sector Q, which represents part of a crown wheel whose axis is the horizontal line AX. The sector Q is carried by an arm L which is pivoted to the bracket M on the axis AX. The arm L carries a slide for the tool T which is again straight sided and represents a crown wheel tooth. Suitable mechanism is provided to reciprocate the tool head along its slide. The bracket M and arm L can be rotated about a vertical axis through A in order to enable the tool to be gradually fed into the blank to the proper depth. To enable this to be done the sector Q is actually separate from the arm L and is connected to it by a sliding joint. When the tool has been fed in to the proper depth the line of stroke of the corner of the tool will move parallel to the line AY at the

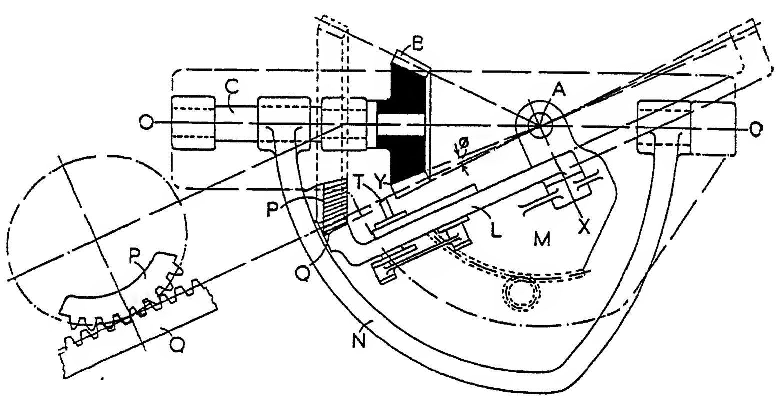


FIG. 275.

bottom of the tooth space, while the axis AX will be perpendicular to the pitch cone of the blank. The generating motion is given by raising and lowering the arm N; this rotates the blank about the axis OAO and the tool, that is, the imaginary crown wheel, about the axis AX, the relative motion being regulated by the sectors P and Q so that it is the same as would occur if the pitch cone of the blank engaged the pitch surface of the generating crown wheel without slip. Actually two tools are used, one for one side of a tooth and the other for the other side. The tools are reciprocated in synchronism, one performing its cutting stroke while the other makes its return stroke. The two tools are both carried on slides on the arm L and receive the generating motion together. The tool slides are adjustable relative to the arm L to allow for the variations in the angle ϕ with teeth of different pitches; they are also adjustable, separately, about a horizontal axis through A to allow for variations in tooth thickness.

Spiral Bevel Generating Machines. In principle these differ from straight bevel generating machines merely in employing a generating crown wheel whose teeth are either curved as indicated in Fig. 276, *a*, or are straight but not radial, as indicated at *b*. The curved teeth may be circular arcs as shown or some arbitrary shape. The realisation of the principle in an actual machine is not altogether easy. Considering teeth of the type given by the crown wheel *b* in Fig. 276, such teeth could be generated in a machine of the type indicated in Fig. 274 merely by swivelling the tool slide round so that its line of stroke no longer passed through the apex A but, so far as the writer knows, such a machine has never been made. Teeth of the type given by the crown wheel *a* in Fig. 276 could be obtained in machines of the types indicated in Figs. 274 and 275 by superimposing on the generating motion of the blank a rotation that is synchronised with the reciprocation of the tool. Such machines have been used but are of very little importance at the present time. The only machine that is of any real importance now is the Gleason. This employs an imaginary crown wheel whose teeth are circular arcs as at *a* in Fig. 276. The teeth of this crown wheel are straight sided and are represented by continuously rotating cutters. The arrangement is indicated quite diagrammatically in Fig. 277. The cutter is carried in the face of a disc B which can rotate about an axis ZZ so that the tool sweeps across the face of the blank. The cutter head is carried in an arm C which is pivoted about the horizontal axis OX which is the axis of the imaginary crown wheel. The arm C is geared to the spindle carrying the blank so that the relative motion is the same as would occur if C were fixed to the imaginary crown wheel and the pitch surface of the latter rolled without slip on the pitch cone of the blank. The generating motion is given by rotating the arm C up and down. The blank is carried in a saddle D which is pivoted to the frame on a

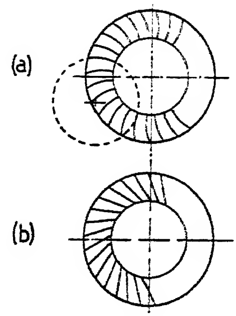


Fig. 276.

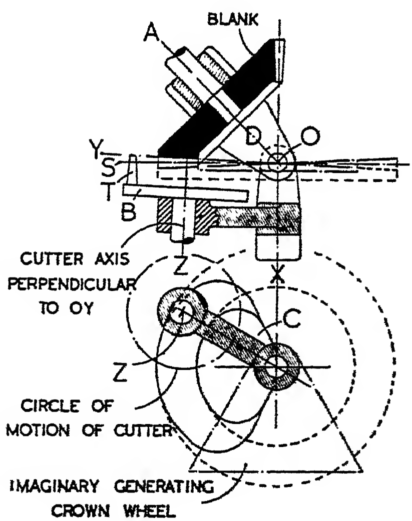


Fig. 277.

vertical axis passing through O. This enables the cutter to be fed into the blank to the required depth; when this has been done the axis ZZ must be perpendicular to the line OY drawn through the bottom of the tooth space and the axis OX must be perpendicular to the pitch cone OS of the blank. In the actual machine the cutter head has twenty to thirty cutters, half of which generate one side of a tooth and the other half the side of the adjacent tooth.

Hypoid Gears. Consideration of these is beyond the scope of this book, but it may be remarked that from the manufacturing point of view they are closely related to spiral bevel gears and are cut on similar machines. Hypoid gears are used chiefly by the motor industry and their production is a much more specialised thing than spiral bevel gear production although that is largely done by specialist firms.

Skew Gears. These, from the point of view of manufacture, are identical with either helical toothed spur gears, or worm gears, and need not be separately considered.

Worm Gears. These may be divided into parallel type worm gears and hour-glass or globoidal type worm gears. In respect of volume of production the latter is at present relatively unimportant and will not be considered. The parallel worm is a form of screw and can be cut in a lathe just like any other screw, but although small worms, such as are used in instruments, etc., and which have helix angles of the order of 80 degrees are cut in that way the worms used for power transmission and which have helix angles ranging from 45 to 75 degrees, are all cut on special worm milling machines. These consist of a bed whose top surface provides ways for the work table to slide on and which also carries the cutter head. The latter can be adjusted in and out perpendicular to the work-table ways and carries a swivelling head in which is mounted the cutter spindle. The work table carries a headstock, in which is mounted the work driving spindle and which houses change gears for varying the speed of rotation of the work, and a tailstock—the work being supported between centres. The work table motion is controlled by a lead-screw which is geared to the headstock spindle. The axial travel of the work is thus related to the rotation of the work so as to give the correct helix angle. The work is cut by a rotating milling cutter carried on the cutter spindle which is driven by a suitable mechanical drive, while the spindle axis is tilted, by swivelling the cutter head, so as to bring the plane of the cutter tangential to the helix being cut. The headstock incorporates indexing mechanism so that when one thread has been cut the work can be indexed and the next thread cut. The worm, after heat treatment, is subsequently ground on a similar type of machine but having a grinding wheel in the place of the milling cutter. The worm wheel is cut by means of a hob which differs from the worm

only in having a slightly greater outside diameter (so as to provide a clearance at the bottom of the wheel tooth space), in being tapered at one end, and, of course, in being gashed and relieved. This hob is mounted at the correct centre distance L from the blank, as shown in full line in Fig. 278. External gearing connects the hob and blank spindles and the hob is rotated so as to give a suitable cutting speed. The hob is then fed axially until it reaches the position shown in dotted outline. The gear ratio between the hob and blank spindles must take into account the number of teeth in the wheel being cut, the number of starts in the hob, and the axial feed of the hob per revolution.

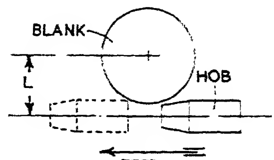


Fig. 278.

Let N = number of teeth in wheel.
n = number of starts in hob.
S = speed of wheel in r.p.m.
s = speed of hob in r.p.m.
A = axial feed of hob in inches per minute.
a = axial feed of hob in inches per revolution of hob.
L = lead of hob in inches.

Then, if the hob rotated but did not move axially,

$$S_1 = s \times \frac{n}{N}.$$

While if the hob moved axially but did not rotate

$$S_2 = A \div \text{circumference of wheel}$$

$$= \frac{A}{N \times \text{Circular pitch of wheel teeth}}$$

$$= \frac{nA}{N \times \text{lead of worm.}}$$

Hence,

$$S = \frac{sn}{N} \pm \frac{nA}{NL}$$

$$= \frac{sn}{N} \pm \frac{nas}{NL}$$

and

$$\frac{S}{s} = \frac{n}{N}\left(1 \pm \frac{a}{L}\right).$$

The plus or minus sign being used according as the rotations due to the rotation and feed of the hob are in the same or in opposite directions.

Chapter 19

THE GRINDING PROCESS. GRINDING WHEELS, ABRASIVES, AND BONDING MATERIALS. TYPES OF MACHINE, AUTOMATIC SIZING. CENTRELESS GRINDING

The grinding process is a method of machining articles by means of abrasive wheels ; it is similar in one respect to the milling process in that it uses a rotating cutter having numerous cutting edges. An abrasive wheel is composed of a large number of abrasive particles held together by a bonding material rather as the aggregate is held in concrete but with the difference that the abrasive wheel has, by design, a number, which may be large, of voids in it. At the periphery of the wheel the particles project, somewhat like the teeth of milling cutters, and these projecting particles remove small chips as they pass over the surface being ground. The chips are usually quite invisible, as such, to the unassisted eye but can be recognised under a microscope. The particles are arranged in the wheel purely by chance and will not, in general, be presented to the work at the best angle, nor will their cutting " edges " have proper clearances ; nevertheless they do their work remarkably well. In due course, however, they become " blunted " and the force that acts on them while they are removing a chip becomes greater than when they were " sharp." In a well designed wheel the bond should be strong enough to hold the particles while they are sharp but should allow them to be torn out when they become blunted, so that other sharp particles can take up the cutting. If the bond is too strong the blunted particles will not be torn out and the wheel will not cut properly ; if the bond is too weak the particles will be torn out too soon and the wheel will wear away too rapidly.

The principal factors entering into the design of abrasive wheels are thus : (1) The nature of the abrasive particle, (2) their size, (3) the nature of the bonding material, (4) the quantity of bond in relation to the number of abrasive particles, and (5) the " structure " of the wheel ; this depends on the proportion of voids in relation to the quantity of bond and number of particles.

Abrasives. The abrasive particles must obviously be harder than the materials they are going to cut and they must have sufficient strength to resist fracture under the suddenly applied forces of the cuts taken. In engineering practice the materials used for abrasive wheels are :

1. Aluminium oxide, Al_2O_3.
2. Silicon carbide, SiC.
3. Diamonds, in the form of " dust."

The aluminium oxide abrasive is found in nature; it forms about 70 per cent of *emery* and 90 per cent of *corundum*; the main supply however, is synthetically made in the electric furnace. The silicon carbide abrasive is not found in nature and is all made synthetically. The synthetic materials have been given a large variety of trade names.

Silicon carbide is harder than aluminium oxide but is not so tough; it is consequently used for very hard materials of medium and low tensile strength, while the tougher and softer aluminium oxide is used for the softer and tougher materials of higher tensile strength. The aluminium oxide material is easier to manufacture and is more widely used than the silicon carbide; it is made in various "strengths." Diamond dust is used only for special purposes.

The larger sizes of abrasive particle are graded into sizes by means of sieves and their sizes are denoted by the number of meshes per inch of the sieve they will just pass through. These numbers are referred to as *grit* or *grain* numbers and range from 8 to 240. Particles finer than 240 are graded by flotation and precipitation methods and are known as *flours*; they are also given numbers according to their fineness. The range of grit sizes marketed by the Norton Company is given below:

Very coarse	*Coarse*	*Medium*	*Fine*	*Very fine*	*Flours*
8	12	30	70	150	280
10	14	36	80	180	320
—	16	46	90	220	400
—	18	60	100	240	500
—	20	—	120	—	600
—	24	—	—	—	—

The grain sizes used in abrasive wheels for engineering purposes mostly lie within the following limits:

Roughing	20–36
Commercial finish	46–80
Ultra-fine finish	100–500

Bonding Materials and Bonds. These are five in number, namely:

1. The vitrified bond.
2. The silicate bond.
3. The rubber bond.
4. The shellac bond.
5. The bakelite bond.

The vitrified bond is composed of certain clays (felspars and kaolin) which when heated fuse into a glass-like mass. The process is a lengthy one and may take up to six weeks to complete but, nevertheless, this bond is the one chiefly used for the abrasive wheels used in grinding machines. It is generally rather more open in structure than the silicate bond. The silicate bond is composed of silicate of soda and the process is a comparatively quick one, manufacture being possible in as short a

time as four days. The silicate bond is closer than the vitrified bond and gives wheels having a milder action; it is consequently used for fine-edged tools, razors, etc., but is little used for the wheels used in machine shops. Very large wheels are usually silicate bonded. The rubber bond is composed of vulcanised rubber and is the strongest of all the bonds; it is consequently used for thin wheels subjected to side forces. The shellac bond is also used for thin wheels and where a fine finish is required. The bakelite bond is also a very strong bond and is used for the fettling wheels used in foundries and for very thin cutting-off wheels.

The "Grade" of an Abrasive Wheel. The quantity of bonding material used in relation to the quantity of abrasive particles is the principal factor determining the force necessary to wrench the particles out of a wheel and this determines the *grade* of the wheel. When the particles are easily torn out the wheel is a "soft" one, when much force is necessary the wheel is "hard." The grades of wheels are indicated by letters but different firms employ different systems. The Norton Company's grading is as follows:

Very soft	*Soft*	*Medium*	*Hard*	*Very hard*
E	H	L	P	T
F	I	M	Q	U
G	J	N	R	W
	K	O	S	Z

while the Carborundum Company's is given in the table below:

	Vitrified and silicate	*Shellac*	*"Redmanol"*	*Rubber*
Very hard .	D, E	—	—	A
Hard . . .	F, G, H	1, 2	3, 4, 5	B, C, D
Medium . .	I, J, K, L, M	3, 4, 5	6, 7, 8, 9, 10	E, F
Soft . . .	N, O, P, R, S, T	6, 7, 8, 9	11, 12, 13, 14, 15, 16	—
Very soft . .	U, V, W	10	17	—

Grading of wheels is not actually done on a composition basis but by means of an indentation test which need not be here considered. In general the harder the work being ground the softer the grade of wheel that is used; this is seen to be reasonable when it is remembered that the harder the material being cut the sharper must be the cutting implement and the sooner the cutting edge will be blunted.

Wheel Structure. This depends on the proportion of voids to bond and abrasive and on the degree to which the materials are packed together. Generally speaking an open structure gives a softer wheel than a close structure, other factors being the same. An open structure facilitates rapid stock removal because it allows room for the "chips" removed

and reduces the tendency for the wheel to become clogged. The Norton Company designates their structures as follows:

Close spacing	0, 1, 2, 3
Medium spacing	4, 5, 6
Wide spacing	7, 8, 9, 10, 11, 12

the structure number following, and the grit number preceding, the grade letter. Thus 46–P.5 designates a wheel of 46 grits, P grade, and number 5 structure. A letter following the structure number or grade letter indicates the type of bond used, while a number preceding the grit number indicates the kind of abrasive particle employed. Thus 3860–L.5.B indicates the use of number 38 " alundum " (Al_2O_3) abrasive (a harder, more brittle kind than the standard type), and the letter B the use of the B-type vitrified bond. Other bond letters are: R for rubber, L for shellac, T for bakelite. The absence of a bond letter indicates the use of an ordinary vitrified bond and the absence of a number in front of the grit number indicates the use of the ordinary grade of alundum.

The Speeds of Grinding Wheels. The speed at which an abrasive wheel can safely be run depends primarily on the strength of the bond. For the vitrified bond the maximum is about 7,000 ft. per minute (peripheral speed) but segmented wheels may be run up to 9,000 ft. per minute. The shellac, rubber, and bakelite bonds may be run at speeds up to 16,000 ft. per minute. Most wheels have the safe speed marked on them in addition to the grit and grade symbols. It is generally considered that wheels should be run at the maximum safe speed, but some authorities state that the speed should be lower the longer the arc of contact between the wheel and work. H. H. Asbridge[1] quotes the following speeds as desirable:

External grinding:	(*a*) large wheel, small work . .	5,000–6,000 ft. per min.
	(*b*) Work larger than wheel . .	3,500–4,500 ,,
Internal grinding	. . . .	2,000–3,000 ,,
Surface grinding	. . . .	3,000–4,000 ,,

Mr. Asbridge makes no mention, however, of the depth of cut, which determines the arc of contact. It should be remembered that the stress in a wheel due to its rotation varies at the *square* of the peripheral speed. Wheels are carefully balanced by the makers and should run true when mounted in the grinding machine, within a few thousandths of an inch or so; the final truing to prepare the wheel for grinding work is done by a diamond held in a fixture on the work table of the grinding machine and traversed across the wheel face until the latter has been trued all over. The diamond cuts through the abrasive particles much as a lathe tool cuts through metal. The truing diamond should not be extremely pointed or the wheel will be finished with a series of ridges (unless a very

[1] Proc. I. Mech. E. Vol. 41, page 40.

slow traverse is used during truing, which would waste time) and the initial wheel wear will be high. Also, after truing it is sometimes beneficial to give the wheel a rub with an oil-stone slip ; this removes any slightly loose particles which might otherwise get jammed between the wheel and the work and cause scratches. The wheel must be trued at intervals because accurate work with a good finish cannot be done with an untrue wheel.

The Cylindrical Grinding Machine. Abrasive wheels are used in grinding machines and these may be classified in the same way as machines using " cutting tools " ; thus the cylindrical grinding machine is the abrasive wheel equivalent of the lathe. Cylindrical grinders are made in

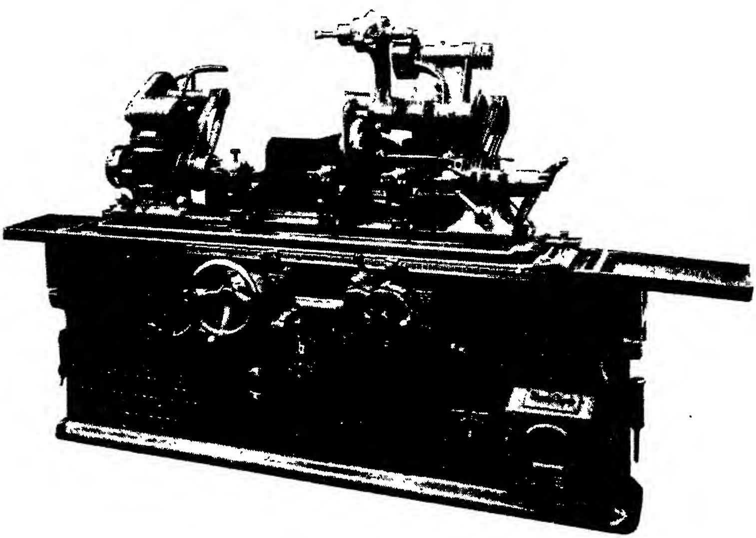


FIG. 279.

several different forms, but these can be roughly divided into (*a*) *plain*, and (*b*) *universal* machines, the former being simplified versions of the latter and capable of only the simpler operations. The plain machine is, however, more robust than the universal one and can take heavier cuts and produce work at a more rapid rate ; it is consequently the machine used for the general run of work in quantity production.

A universal cylindrical grinding machine is shown in Fig. 279. It consists of a heavy bed whose upper surface is accurately machined to form ways upon which the work table, made in two parts, can slide to and fro. In modern machines the reciprocation of the table is obtained by hydraulic mechanism as this gives a smoother motion than the rack and pinion drives formerly used. In the machine illustrated the speed of traverse can be anything from 6 to 240 in. per minute. The upper

part of the work table can be swivelled about a vertical axis relative to the lower part in order that tapered work may be ground. The maximum included angle that can be ground by this means is not usually greater than 15–20 degrees. The work table carries a headstock with a live spindle at the left-hand end and a tailstock with a spring-loaded, or sometimes an hydraulically operated, poppet at the right-hand end, both units being adjustable to any position along the table. The headstock consists of two main portions the upper of which, carrying the spindle bearings and variable speed driving motor, can be swivelled through any angle up to 90 degrees relative to the lower part; this enables tapers with an included angle greater than 15–20 degrees to be ground if the work can be held in a chuck. The wheel spindle is carried in bearings in the wheel head, the bearings being specially designed to reduce the working clearance to the minimum. The wheel head is supported on a compound slide. The top portion carrying the wheel spindle can be swivelled on an intermediate member which can slide along a lower member. The latter in turn can be swivelled on the bed of the machine. The cross-feed of the wheel-head can thus be arranged at any angle to the work-table ways; also the wheel spindle axis can be at any angle to the wheel-head slide. The feed to the wheel head may be given, either by hand or by means of a mechanically operated ratchet mechanism, at one end only of the traverse of the work or at both ends. The reversing mechanism of the work-table traverse motion can be arranged to provide a "dwell" at one or both ends of the motion. An internal grinding spindle is permanently mounted on the wheel head and may be swung into the working position in a few moments. A tank to contain coolant and a pump to supply it to the work-wheel contact are provided.

In plain machines neither the headstock nor the wheel-head slides can be swivelled, and the work table may not be capable of swivelling either. The wheel spindle axis can usually, however, be set round at any angle to the work-table ways. Thus plain machines may not be capable of grinding tapers except by the method described in a later section.

In very large machines the wheel head is generally carried on ways so that it can be traversed to and fro instead of traversing the work table. The headstock and tailstock are then secured directly to the bed of the machine.

Methods of Holding Work. These are very much the same as in lathe work; the principal method is between centres, but hollow work may be held on a mandrel and short work in a chuck. Long slender work must be supported by means of steady rests; the parallelism of such work depends primarily on the skilful adjustment of the steadies.

Plunge-Cut and Traverse Grinding. The work may be ground to size in two ways: one method, which is known as *plunge-cut* grinding, uses a wheel whose face width is equal to or slightly greater than the

length of the surface being ground, and feeds this wheel in radially towards the work, which is not traversed at all although the wheel may sometimes be given an axial oscillation of about $\frac{1}{32}$ in. amplitude. The cylindricality of the work then depends directly on that of the wheel. This method is used chiefly in quantity production on plain machines and wheels up to 18 in. in width may be used. The second method uses a wheel whose width is only a fraction of the length of the work and traverses the work to and fro past the wheel or, alternatively, the wheel head past the work. In this method, which is the more common one, the cylindricality of the work does not depend directly on the truth of the wheel, but although an untrue wheel might be made to produce accurate work it would take an inordinate time to do so and would be hopelessly uneconomic.

The Accuracy attainable in Traverse Grinding. At first glance it might be thought impossible to produce really accurate work when the cutting implement, the grinding wheel, must wear away during the cutting operation. It can easily be seen, however, that wheel wear does not limit the accuracy attainable in the least degree. Consider a piece of work C, Fig. 280, and suppose the wheel to be fed in an amount x at the beginning of a traverse from A to B. When the wheel arrives at B it cannot have worn away by more than the amount x or it would not be touching the work at all. Hence by making the "cut" x as small as we please we can reduce the inaccuracy due to wheel wear to as little as may be required. The accuracy attainable depends primarily on the accuracy of the machine and on its proper manipulation. Tolerances of $\pm 0{\cdot}0002$ are easily worked to on any good machine.

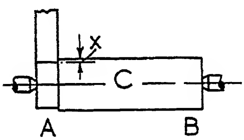


Fig. 280.

Work Speeds, Cuts, and Rates of Traverse. Considering the last of these factors first it should be such that the traverse *per revolution of the work* is equal to about three-quarters to seven-eighths of the width of the wheel being used. If a low speed of traverse is used (in relation to the work speed) the cutting will be concentrated on the edges of the wheel, which will tend to become rounded or crowned. A very slight crowning will produce a spiral marking on the work which is objectionable. On finishing cuts the rate of traverse is usually reduced considerably, but since the cuts then taken are very small no trouble is experienced from crowning.

The work speed and depth of cut have been shown by J. J. Guest [1] to be bound up together so that they cannot rationally be considered separately; for a full consideration of the theory of grinding evolved by Guest, the reader is referred to his book; only an outline can be given

[1] "Grinding Machinery." J. J. Guest. Edward Arnold & Co.

here. Fig. 281 shows a grinding wheel taking a cut whose thickness t has been greatly exaggerated. The length of the arc of contact AB can be shown to be given by

$$\text{Arc AB} = \sqrt{\frac{Ddt}{d \pm D}}$$

and the angle α by $$\alpha = \sqrt{\frac{d \pm D}{dD} \cdot t} \text{ approximately}$$

where D = diameter of wheel and d = diameter of work.

The plus sign applies to external grinding (as shown) and the minus sign to internal grinding. Suppose the abrasive particle which sweeps out the path AB is followed by another particle C which will sweep out the path DE; then the interval of time T between the moment when the particle A was at B and the moment when C and E both arrive at B is given by T = arc BE/v where v is the peripheral speed of the work. But this interval is easily seen to be equal to the interval during which the particle C moves to A.

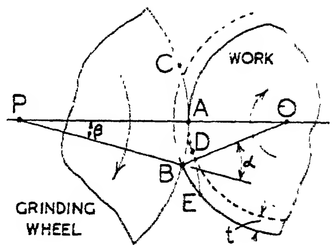


Fig. 281.

Hence $$T = \frac{CA}{V} \text{ where V = peripheral speed of wheel,}$$

and thus $$BE = vT = \frac{v}{V} \cdot AC.$$

Now, referring to Fig. 282, the maximum thickness of the chip is BF and, assuming BEF to be a right-angled triangle, BF = BE sin α or, since α is, actually, quite small,

$$BF = BE \cdot \alpha$$

$$= \frac{v}{V} \cdot AC \cdot \alpha$$

$$= AC \times \frac{v}{V}\sqrt{\frac{d \pm D}{dD} \cdot t}.$$

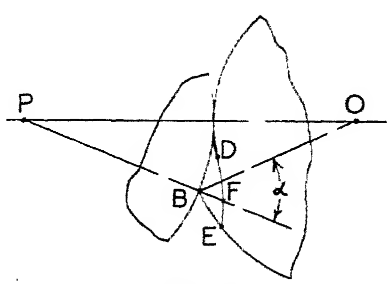


Fig. 282.

But the projecting portions of the abrasive particles are, on the average, approximately triangular in shape and so the cross-sections of the cuts they take are also approximately triangular. Hence the cross-sectional area of the cuts is proportional to the square of the thickness of the chip. That is, maximum cross-sectional area of chip

$$A_{max} = \frac{kv^2}{V^2}\left[\frac{(d \pm D)}{dD} \cdot t\right]$$

where k is a constant whose value depends on the spacing of the abrasive particles in the wheel. The force acting on the particles may be assumed proportional to the cross-sectional area of the chip, and if that force is too great the abrasive particle will be torn out. Hence the expression[1] $\left(\frac{kv^2t}{V^2}\right)\left(\frac{d \pm D}{dD}\right)$ affords a criterion for determining whether the abrasive particles will be torn out while they are still sharp or whether they will remain held in by the bond. If the value of the expression, which may be called *Guest's criterion*, exceeds some amount depending on the strength of bond of the wheel the latter will wear excessively. On the other hand, if the forces acting on the abrasive particles are too small the particles will never be torn out and the wheel will glaze ; hence there is a minimum value for the expression below which glazing will occur. If a wheel tends to wear too rapidly the conditions (work speed v and depth of cut t) must be changed so as to reduce the value of Guest's criterion ; this may be done by decreasing either v or t but, since the criterion depends on the square of v and on only the first power of t, a given percentage reduction in the work speed is more effective than the same percentage reduction in the depth of cut. Similarly if the wheel tends to glaze then either v or t must be increased.

The rate at which metal is removed from the work is equal to vtw where w is the width of the wheel, and the power absorbed can be assumed proportional to the rate of removal of metal. Now the power available is limited by the power of the driving motors of the machine and has a fairly definite maximum value. Hence the expression vtw must not exceed some value C depending on the power supplied to the machine. Therefore, *assuming full power to be used*, $vt=\frac{C}{w}$ and, on substituting this in the criterion it becomes $\left(\frac{kCv}{wV^2}\right)\left(\frac{d \pm D}{dD}\right)$. Supposing the best value for this criterion (that just below the value giving excessive wear) to be E then

$$E=\left(\frac{kCv}{wV^2}\right)\left(\frac{d \pm D}{dD}\right)$$

and

$$v=\left(\frac{wEV^2}{kC}\right)\left(\frac{dD}{d \pm D}\right).$$

Thus for a given wheel and a given work diameter the work speed depends on the power supplied to the machine, the greater that power the lower the work speed. This may seem anomalous until it is remembered that $vtw=C$ and so the reduction in work speed v consequent upon

[1] As deduced by Guest the criterion does not contain the term V^2 in the denominator, but this is, I think, because he is assuming V to be made as great as considerations of strength, etc., permit, and is not regarding it as being a variable capable of being changed in order to vary the action of the wheel.

the increase in the power factor C involves a greater increase in the depth of cut t. Again, supposing all the other conditions to remain unchanged, an increase in the wheel width w will necessitate an increase in the work speed v accompanied by a corresponding decrease in the depth of cut t.

Considering the effect of work and wheel diameters it will be seen that in external grinding, where the work diameter d is usually much less than the wheel diameter D, Guest's criterion becomes, approximately, $\frac{kv^2t}{V^2d}$, which indicates that as the work diameter decreases the value of the criterion increases and, in order to keep it within the upper limit beyond which wheel wear will be excessive, the work speed or depth of cut, or both, must be reduced. In internal grinding, where D is smaller than d the criterion approximates to $\frac{kv^2t}{V^2D}$ which indicates that with a small wheel the work speed and depth of cut may have to be reduced to avoid excessive wheel wear.

For a fuller consideration of the theory of grinding the reader is referred to Guest's book and also to a paper by R. V. Hutchinson in *Trans. S.A.E.*, March, 1938.

In practice work speeds range from 10 to 70 ft. per second, and for finishing cuts are sometimes made 25–50 per cent higher than for roughing. The cuts taken during roughing range from as little as 0·0005 in. on small work up to as much as 0·005 in. on large work and with heavy machines. Finishing cuts are of the order of 0·0005 in. or less and the last three or four traverses of the work may be given without putting on any cut; the wheel will generally take a very fine cut during these final traverses because of the very slight spring of the work and the machine under the forces due to the preceding cuts. This procedure is sometimes referred to as "sparking out" because the sparks due to the cutting action of the wheel gradually fade out during the last few traverses. It has been established that when a wheel is only just "sparking" the cut it is taking is only about 0·00001 inch.

In cylindrical grinding the directions of rotation of the work and wheel are usually as indicated in Fig. 281, but sometimes the work rotates in the opposite direction to the wheel. The allowances left on turned work for removal during grinding are usually about 0·005 in. to 0·020 in. depending on its diameter and length and on the kind of finish left by the previous operation. Work is frequently rough ground on one machine and finish ground on another; the finish grinding allowance will then usually be about 0·002 in.

Examples of Cylindrical Grinding Work. In Fig. 283 a method of grinding a taper on work held between centres is shown. The wheel-head slide A is swung round through the semi-apex angle of the taper α,

and the wheel is traversed to and fro parallel to the face of the taper by the cross-feed mechanism. The cut can be put on, and the size regulated, by moving the work table; normally the work table is locked while taper grinding by this method is done. In a plain machine in which the wheel head can be swivelled, but not the wheel-head slide, the example just considered could be done only by employing a wide wheel and taking a plunge cut. Fig. 284 shows two methods of grinding a shoulder or flange at the same setting as the cylindrical part of the work. At (*a*) the wheel axis is parallel to that of the work and the squareness of the shoulder with the shaft depends largely on the accuracy of the dressing of the side of the wheel. Better results can be obtained by slightly recessing the side of the wheel and then finishing the shoulder by cross-feeding the wheel head. In these methods the arc of contact when grinding the shoulder may be very long and this may cause trouble through overheating; it is not unknown for hardened work being ground in this way to be softened by the heat or even for pieces to break out of the surface. The method shown at (*b*) is much to be preferred; here the wheel axis is swivelled round and the wheel is dressed to the angular shape shown. If the face X of the wheel is wide enough then the shoulder can be finished by a plunge cut, but otherwise the cross-feed of the wheel head must be used. For special purposes where numerous shoulders must be ground plain machines are built with the wheel axis set round at 45 degrees to the work-table ways. Special wheels, which are in effect two wheels as

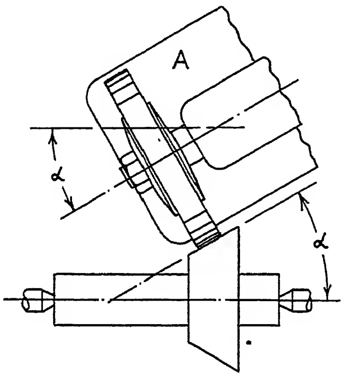


FIG. 283.

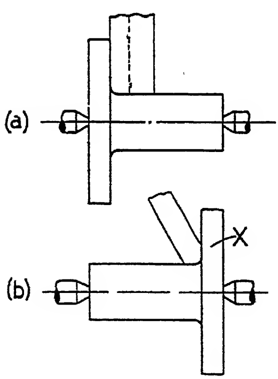


FIG. 284.

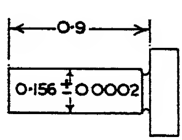


FIG. 285.

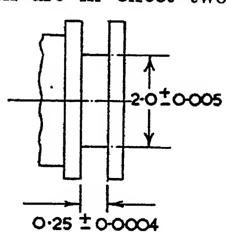


FIG. 286.

indicated by the dotted line in Fig. 284*a*, are obtainable and are sometimes used, when fillets and shoulders have to be ground, in order to reduce the amount of dressing necessary on the corner of the wheel.

Figs. 285 and 286 show two examples of plunge cut grinding on semi-automatic machines. The former is done in 12 secs. and the latter in 17 secs.

Internal Grinding. This can be done on ordinary cylindrical grinders if they are fitted with an internal grinding spindle, but just as the boring machine is better adapted for boring operations than is the lathe so the internal grinding machine is better able to do internal grinding than is the ordinary cylindrical grinder.

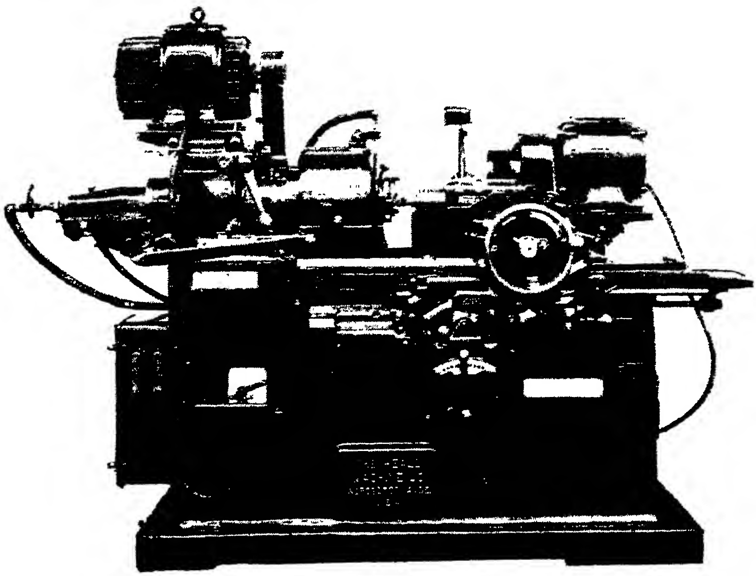


FIG. 287.

Internal grinding machines may be divided into two groups: (*a*) in which the work rotates, and (*b*) in which the work does not rotate. An example of the first type is shown in Fig. 287. The work is held in a chuck on the spindle of the work head seen at the left, while the wheel spindle is carried on a slide which can move across the saddle which is seen on the machine bed. The saddle can travel to and fro on the bed ways and is actuated hydraulically. The universal machine differs from the plain one illustrated chiefly in that the work head is carried on a swivel so that the axis of rotation of the work can be placed at an angle to the bed ways and thus taper holes can be ground. In these machines the work head is sometimes carried on a cross-slide at right angles to

the bed ways, while the wheel spindle is carried direct on the saddle. In machines of the second type, group *b*, the work is held on a table which can be traversed to and fro parallel to the axis of the wheel spindle which rotates in bearings in a large cylindrical member which itself can rotate in bearings in the frame of the machine. The axis of rotation of the member carrying the spindle bearings is made to coincide with the axis of the hole being ground and means are provided to enable the distance between that axis and the axis of rotation of the spindle to be varied so as to regulate the size of the hole being ground. The grinding wheel in these machines thus has a planetary motion and the machines are sometimes called " planetary type " machines ; they are obviously best adapted to the grinding of holes in unsymmetrical bodies which would be difficult to rotate, but such work is now commonly " honed " (see Chapter 18).

In internal grinding the wheel must necessarily be smaller than the hole being ground and thus very small wheels are often inevitable and, in consequence, spindle speeds may be very high, sometimes reaching 30,000 r.p.m. These high speeds, in conjunction with the limited space available, make the design of internal wheel spindles very difficult and considerations of rigidity limit the depth of hole that can satisfactorily be ground to about 6–8 diameters. Beyond this limit the accuracy attainable falls off rapidly and so deep holes are not usually ground but are honed, since, as will be seen later, the honing process is not subject to this limitation.

Automatic Sizing. In recent years much progress has been made in the direction of making grinding machines automatic and at the present time many machines, particularly internal ones, are fully automatic except for the insertion and removal of the work. In order to obtain automatic operation it is necessary to have a device to regulate the size of the work and to maintain it within the prescribed limits regardless of wheel wear ; some of these devices will now be described.

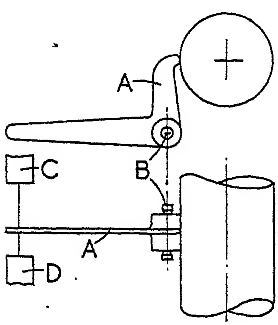


Fig. 288.

The principle of the " Precimax " automatic sizing mechanism developed by John Lund, Ltd., of Keighley, is indicated in Fig. 288. A bell-crank lever A is pivoted at B and one arm, provided with a diamond rubbing tip, bears on the work being ground. The other arm is arranged to intercept the rays of light passing from a source C, which otherwise would fall on the photo-electric cell D, when the work reaches the right size. Interception of the light rays produces a change of current through the photo-electric cell and, after amplification, this change is used to

stop the in-feed of the grinding wheel and to bring about the withdrawal of the wheel head. If it is desired the work can be made to perform any specified numbers of traverses after the wheel feed has been stopped, in order to enable any slight spring of the work and machine to be eliminated and the wheel to "spark out." With this device work can be obtained to limits of $\pm 0{\cdot}0001$ with great regularity and speed; the wheel must be dressed occasionally by the operator in order to maintain a good finish on the work.

In the Heald internal grinding machines the work size is automatically

Fig. 289.

kept constant by feeding the wheel forwards by a very small amount, just before the final traverses are given, and dressing it by a diamond whose position relatively to the axis of the work spindle is fixed according to the size of the hole being ground. By giving a fixed number of traverses after the wheel had been dressed the work size can be maintained within close limits.

In another system the in-feed of the wheel is made automatic and a plug gauge with two steps is automatically, and at short intervals, pressed against the back end of the hole being ground; when the first step of the gauge enters the hole the in-feed of the wheel is stopped, the wheel is

dressed by a diamond, and then the in-feed is started again and continues until the second step of the gauge enters the hole ; the machine then stops. The principle of the Solex pneumatic gauge (see p. 310) has recently been applied in an automatic sizing mechanism.

Fig. 289 illustrates the Pratt continuous gauge now being used extensively on cylindrical grinding machines. It enables a continuous indication of the work size to be observed during grinding.

Surface Grinding. Machines for grinding plane surfaces are very widely used and may be divided into two distinct groups : (*a*) Those in

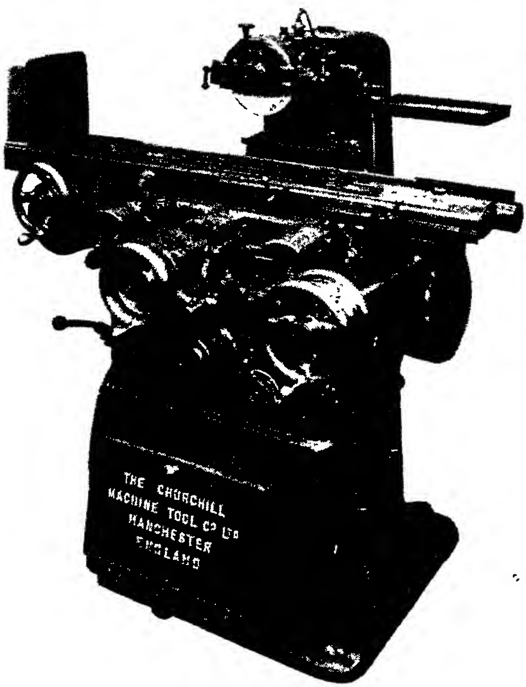


FIG. 290.

which the edge of the grinding wheel is used, and (*b*) Those in which the face of the wheel is used.

In the first group the wheel is narrow compared with the work and the plane surface is obtained by traversing the work to and fro beneath the wheel and by feeding the work (or sometimes the wheel) across perpendicular to the direction of traverse, by an amount nearly equal to the width of the wheel, between the traverses. This type of machine is built in several forms ; a typical small machine is shown in Fig. 290. The work table reciprocates on ways on the saddle which itself slides on ways on the bed in a direction parallel to the wheel spindle. The latter is carried in a head which can slide up and down long vertical ways

formed on the back of the bed casting. In rather larger machines the work table slides directly on the bed ways and the wheel is carried in a head that can be moved horizontally perpendicular to the bed ways. The wheel head in turn is carried in a saddle that can slide up and down the face of a column fixed to the bed. For certain special work such as piston rings, circular saws, and discs, etc., the work table is made circular and rotates instead of reciprocating. Very large machines of the edge wheel type are built rather like planing machines with a cross-beam carried on columns on either side of the work table.

In the second group the wheel diameter is made greater than the width of the work being ground and the work is traversed to and fro past the wheel which is fed axially (that is, perpendicularly to the surface being ground) in order to put on the cut and to regulate the size of the work. In this type of grinding the arc of contact between the wheel and the work may be very long compared with the lengths met in edge-wheel grinding. Long arcs of contact generally imply great heating of the work unless special precautions are taken, and in surface grinding with face wheels the supply of coolant must be plentiful and coarse grit, open structure, soft grade wheels must be used. Segmental wheels are very commonly used. Face-wheel surface grinding is much quicker than edge-wheel grinding and it is used chiefly for quantity production manufacturing work; it is not usually considered capable of producing work to such narrow limits as are possible with edge-wheel grinding.

Face-wheel surface grinders are built in several forms. In one form the wheel spindle is vertical and is carried in a head that is adjustable vertically on the column of the machine; the work table reciprocates on the bed ways. In another form the work table again reciprocates but the wheel spindle axis is horizontal and the work is ground on its vertical face. In a third form the work table is circular and rotates about a vertical axis underneath the wheel, whose axis is also vertical; machines of this kind have been built with two wheel spindles, the roughing cut taken by one wheel being followed immediately by the finishing cut of the second wheel.

Holding the Work in Surface Grinding. The commonest method is by means of a magnetic chuck; this is nothing more than a multi-polar magnet whose surface is accurately flat to receive work and which is adapted to be clamped to the machine table. The magnet is usually an electro-magnet but, with the development of improved magnet steels, permanent-magnet magnetic chucks can now be made satisfactorily. The chucks are bolted to the tables of the machines and hold the work by magnetic attraction. In some machines the magnetic chuck is built in as an integral part of the work table. Magnetic chucks are sometimes used on cylindrical grinding machines. Generally speaking, work that has been held on a magnetic chuck must be demagnetised on a

demagnetising fixture after grinding. Other methods of holding the work are similar to those used in shaping and planing machine practice.

Centreless Grinding. In this process the work is supported by a support blade and is held up to the grinding wheel by a regulating wheel as indicated in Fig. 291. The speed of rotation of the work is determined by that of the regulating wheel and may range from 50 to 200 ft. per minute. The supporting surface of the support blade is inclined to the line OP joining the centres of the two wheels at some angle α as shown and this angle varies with the work being ground, but is usually between 3 and 20 degrees. The support blade is positioned so that the axis of the work lies slightly above the line OP except in machines operating on long bars or rods, when the work centre is kept below the line OP. Raising the axis of the work speeds up the rounding action,

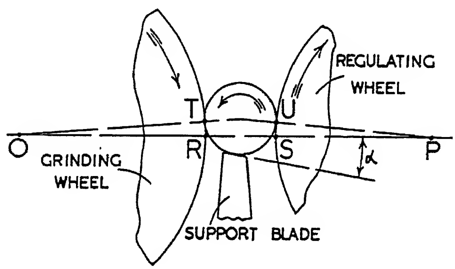


FIG. 291.

which occurs roughly as follows. Suppose the work to have a high spot on it, then, when that spot comes into contact with the regulating wheel the work will be pushed towards the grinding wheel and a low spot will be formed on the other side of the work, but, *because of the inclination of the support blade surface and because the axis of the work is above the line OP*, the low spot will not be quite opposite the high spot nor will the depth of the " recess " formed be as large as the height of the " bump." When the high spot comes round into contact with the grinding wheel the previously formed low spot will not be in contact with the regulating wheel and so the high spot will be ground off. Now consider a body having a low spot on it. When the low spot comes round into contact with the support blade the work will sink slightly and, since the grinding and regulating wheel surfaces are closer together at RS than they are at TU, the grinding wheel will grind away the work slightly. Thus, whether the work has high or low spots on it, it will ultimately be brought to a circular cross-section and, actually, the process is a rapid one.

The regulating wheel is usually a rubber bonded grinding wheel of fine grit (about 80) and strong bond, but vitrified wheels are also used although they do not give such good surface finishes. The grinding

wheels are selected according to the same general principles as in other grinding operations.

Centreless Grinding Methods. There are two distinct methods of operating centreless grinding machines. One, which is often called the "through-feed" method, keeps the regulating wheel axis fixed in position relative to the grinding wheel and feeds the work through between the wheels parallel to their axes. At each end of the support blade the work is supported in a V-shaped trough, that on the ingoing side having an inclined portion so that the weight of the work resting on it will automatically feed the work in between the wheels. Once the work has been entered between the wheels it is fed through automatically because the regulating wheel axis is, actually, slightly inclined to the grinding wheel axis and support blade surface; hence, as is indicated in Fig. 292, the tangential force between the regulating wheel and the work has a component *f* which can feed the work through. Because of the tilt of the regulating wheel axis that wheel is not made cylindrical; its shape is actually that of a hyperboloid of revolution, but it is obtained quite simply merely by feeding the dressing diamond parallel to the work blade surface. This results in line contact between the regulating wheel and the work whereas, if the former were cylindrical, the contact would be only point contact.

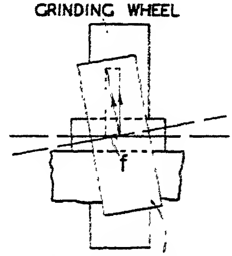


FIG. 292.

In the second method of centreless grinding the regulating wheel is moved back to allow the work to be inserted and is then fed forward slowly until the work is ground to size, when it is moved back again and the work is removed. This method must be used whenever the work has a shoulder or is not a plain cylinder. It is commonly called the "in-feed" or "plunge-cut" method. By suitably dressing the wheels to shape, quite complicated shapes may be ground by this method; an end stop is then required in order to position the work axially. Similarly, by providing suitable external work supports quite heavy and awkward objects, for example, the tubular ends of a motor car rear axle casing, may be centreless ground.

The accuracy attainable in centreless grinding is equal to that obtainable with ordinary grinding but when very close limits are specified it is generally necessary, for the best economic results, to put the work through several machines thereby reducing the corrections to be made in each machine. A motor-car gudgeon pin, for example, might receive three roughing passes each removing about 0·005 in. of stock and then five finishing passes, the stock removed ranging from about 0·0015 in. on the first pass down to 0·0003 in. on the last pass. Such pins are commonly held to limits of $\pm 0{\cdot}0002$ in.

Centreless grinding machines sometimes produce work which though it is constant in diameter is not cylindrical. A three-sided figure of constant diameter is shown in Fig. 293, but the work occasionally produced on centreless grinders will generally have a greater number of "sides." The lack of cylindricality of such work is at once apparent if it is tested, by means of a dial indicator, while it rests on a V-block, as indicated in Fig. 315, p. 308.

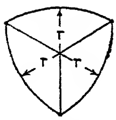


FIG. 293.

The Heald Company has produced an internal centreless grinder in which the work is supported between three support wheels.

One advantage of internal centreless grinding is that concentricity of outside and inside surfaces is automatically ensured.

Tool and Cutter Grinding. These two branches of grinding practice are distinctly separated not only from the machine-shop grinding hitherto considered but also from each other. By tool grinding is meant the sharpening of single-point tools of the lathe type and by cutter grinding the sharpening of all forms of cutter of the milling type, including reamers and twist drills. Tool grinding is nowadays done chiefly "off-hand," this term signifying that the tool is held up to the grinding wheel by hand although it is usually supported on some sort of a rest, as indicated in Fig. 294, which shows a modern four-wheel tool grinder; the rest may be set so as to determine the angle at which the surface of the tool is ground. Grinding is done on both the periphery and on the side or face of the wheel; the former method is faster than the latter and is less likely to introduce trouble due to overheating of the tool but it has the drawback, which may be serious with cemented carbide-tipped tools, that it involves undercutting of the cutting edge as is indicated in Fig. 295. Tool grinding is done both wet and dry, but when water is used it should be plentiful in quantity; a restricted supply is worse than useless and will introduce a great risk of cracks being formed. In grinding cemented carbide-tipped tools it should always be remembered that the tip material is comparatively weak in tension and anything likely to set up tensile stresses should be avoided; for example, grinding a tool with the tip at the bottom as shown in Fig. 296. It is also important that

FIG. 294.

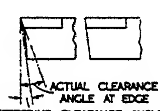


FIG. 295.

tipped tools should not be allowed to become seriously dulled ; frequent light regrinding is much more economical than infrequent heavy grinding. Special wheels are made for grinding cemented carbides and the wheel makers' recommendations should be followed ; grinding them with ordinary wheels is an unsatisfactory procedure. It is important that the grinding wheel should run true and the grinding machine be rigid and free from vibration. In all off-hand grinding operations it is desirable to keep the work moving on the face of the wheel.

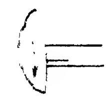


FIG. 296.

Cutter Grinding. This is done on special cutter grinders which may be relatively simple in construction but which tend to become more and

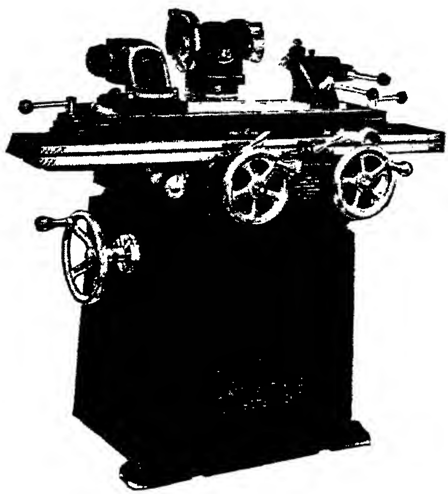


FIG. 297.

more complex as the range of types of cutter they can undertake is extended. A typical machine is shown in Fig. 297. The amounts of metal that have to be removed in cutter sharpening are comparatively small and so cutter grinders are comparatively light in construction ; it is important, however, that vibrations should not occur. Most machines work dry, and soft, free-cutting wheels are used in order to avoid drawing the temper of the cutter edges. Both the peripheries and the faces of disc wheels are used and cup wheels are also employed ; it is important that they should be used in such a manner that the shape of the land

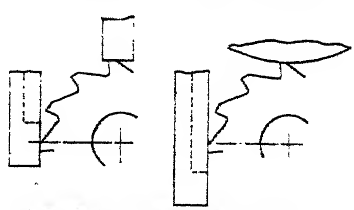


FIG. 298.

of the cutter being ground, and its clearance angle, depends primarily on the setting of the machine and not on the accuracy of truing of the wheel or on the way the wheel wears. Fig. 298 indicates *incorrect* methods at *a* and correct methods at *b*. The correct clearance angle is obtained by setting the cutter properly in relation to the grinding wheel and this is done by means of *tooth rests*, against which the cutter teeth are held by hand, in conjunction with the vertical adjustment of the work table in relation to the wheel axis, as is indicated in Fig. 299, from which it is seen that H, the difference in level of the wheel and work axes, is given by $H = R \sin \alpha$ where R is the radius of the wheel and α is the desired clearance angle.

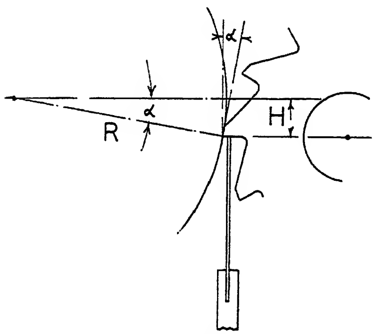


FIG. 299.

In grinding with the cup wheel the tooth being ground should be set

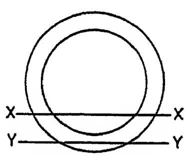


FIG. 300.

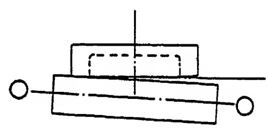


FIG. 301.

so that it intercepts the hollow part of the wheel as indicated by the line XX in Fig. 300, and not as indicated by YY. With long cutters, as for example reamers, the cutter axis OO (Fig. 301) must be set slightly out of square with the wheel axis so as to make the wheel cut on one side only. The necessary clearance angle is obtained by the setting of the tooth rest in relation to the axis of the cutter, as indicated in Fig. 302. The height h is given by $h = r \sin \alpha$ where r is the radius of the *cutter*.

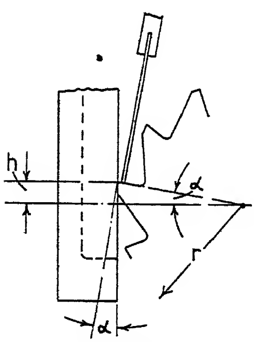


FIG. 302.

Twist Drill Grinding. It has been mentioned that it is important that the cutting edges of a twist drill should be equal in length and equally inclined to the drill axis; the clearances behind the cutting edges should also be equal although, provided the clearance is sufficient, this is a secondary matter. Numerous drill grinding machines

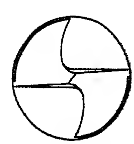


FIG. 303.

are now available which ensure correct grinding of twist drills, but after grinding on these machines it is generally desirable to thin the drill point as indicated in Fig. 303 by off-hand grinding on a cutter grinder.

Miscellaneous Grinding Machines. Special machines are made for grinding crankshafts, camshafts, worms, screw-threads and gear-wheel teeth and splined shafts. Crankshafts are ground by the plunge-cut method and wheels are trued to the correct radii at the corners so as to grind the fillets between the pins or journals and the webs; very large wheels are used partly in order to provide sufficient clearance and partly to increase the output.

The underlying principle of the camshaft grinding machines is shown, diagrammatically, in Fig. 304. The camshaft A rotates between centres in a bracket B, which can swing about a pivot C in a bracket D which is part of, or is bolted to, the work table of the machine. The drive to the camshaft is through a short shaft carried in the bracket B and on which are mounted master cams E which are held up against a follower roller F by a spring acting on the bracket B. The master cams then swing the bracket to and fro so that the grinding wheel grinds the cams to the correct profile. The shape of the master cam is not merely an enlargement of that of the cam being ground, but must allow for the swing of the bracket B and for the difference in size of the follower F and the grinding wheel. If the size of the latter departs appreciably from the size for which the master cam was made the profiles of the cams ground will be inaccurate. The master camshaft has as many cams as the shaft being ground and the follower roller is moved along into contact with the appropriate cam as the shaft is indexed along so as to bring the cams successively in line with the grinding wheel. The machines are made fully automatic except for the loading and unloading. The master cams can be ground to shape by substituting a prototype cam for the camshaft, a steel disc for the grinding wheel and a grinding wheel for the follower roller and by other methods.

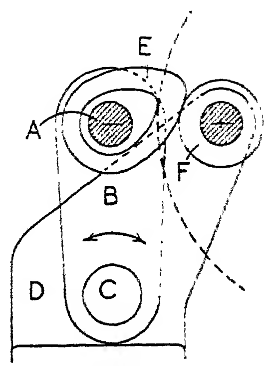


Fig. 304.

There are several methods by which screw-threads can be ground; one uses a grinding wheel having a single " rib " formed to the shape of the thread space and the work is traversed past the wheel several times. The work is, of course, geared to the lead-screw of the work table. Cuts of the order of 0·010 in. deep may be taken, but the crest radius must be ground as a second operation using another wheel. By using a wheel having two or more ribs the crest radius can be ground simultaneously

with the rest of the thread. If a wide multi-ribbed wheel, which is tapered at one end, is used the work need make only a single traverse past the wheel. Comparatively short threads can be machined by a plunge-cut method using a multi-ribbed parallel wheel equal, or slightly greater, in width to the work. The latter rotates quite slowly and makes only a little more than one revolution ; this method is most suitable for threads that run close up to a shoulder. Many problems have had to be solved during the development of the modern thread grinding machine. The chief of these have been the evolution of satisfactory wheels and suitable methods of dressing them to shape. The latter may be done in three main ways : first, by means of a diamond which is guided by a large former or template whose size is reduced by means of a pantograph mechanism ; this mechanism is built as part of the machine and can be brought into action without taking the work out. Secondly, by means of a diamond carried by a fixture on the tailstock of the machine and which is moved in and out, in synchronism with the movement of the work table, by a cam which is geared to the work-table lead-screw. Thirdly, by pressing hardened rollers against the wheel and revolving it slowly ; the rollers are ground to shape by means of wheels formed by one of the preceding methods. Internal thread grinders are available and most machines are fitted with projection enlargers which throw an enlarged " shadow " of the thread profile being ground on to a screen so that the operator can see the progress of the work. In grinding threads from the solid the greatest wheel wear is on the crests of the ribs and to reduce the amount of wheel dressing two wheels mounted a short distance apart on the same spindle may be used or the work may be put through separate machines for roughing and finishing. In the latter case registration of the work with the wheel of the second machine may be obtained by keeping the driving carrier on the work when it is transferred from the first to the second machine. Thread grinding machines have reduced the times required for the production of accurate threads on hardened work to a few minutes and have enabled work to be machined which cannot be done by a die-head.

For a review of the development of thread grinding machines and methods the reader is referred to a paper by S. J. Harley, *Proc. I. Mech. E.*, Vol. 141.

Gear tooth grinding machines may be divided into copying and generating machines. The former use a wheel which is shaped to correspond to the tooth space and the wheel is traversed to and fro parallel to the axis of the gear being ground. The gear is usually indexed one tooth between each complete traverse of the grinding wheel head so as to avoid local heating and to distribute the errors due to wheel wear. The wheel is trued by means of diamonds which are guided by master formers and pantograph mechanism ; the truing mechanism usually operates automatically just before the final cut is taken. One advantage of the formed

wheel type of machine is that modifications to the true involute tooth shape are easily made. Generating gear tooth grinders all use saucer-shaped wheels whose faces are made to represent the straight side of a rack tooth. This imaginary rack tooth is rolled in synchronism with the gear being ground just as the cutter is rolled in the rack cutter type machines. The generating machines may be divided into (*a*) those employing extra large wheels, and (*b*) those employing small wheels in conjunction with special truing devices. In the former the wheel is made large so as to reduce its wear, while grinding a single gear, to negligible amounts and the use of large wheels makes it unnecessary, with the gears that are normally ground, to provide any traverse parallel to the axis of the gear. The generating motion is usually given entirely to the gear being ground. This type of machine cannot grind the smaller of two integral wheels if those wheels are close together. In the machines using small wheels, of which the Maag machines are the principal representatives, it is essential to provide some compensation for wheel wear. In the Maag machines this is done as follows. At frequent intervals a " feeler " diamond is, automatically, moved up until it comes into contact with the operative edges of the wheel. If the latter has worn since the previous dressing by more than a certain amount, the increased travel of the feeler diamond closes electrical contacts which causes the wheel to be fed axially by a small amount and then to be trued by a diamond whose position ensures that the face of the wheel is kept coincident with the side of the imaginary rack tooth. Two wheels are used in the Maag machines, one operating on one side of the teeth and the other on the other side. Each wheel has its own compensating device. The generating motion is given entirely to the gear, which is also traversed to and fro axially.

Splined shafts are usually ground by means of formed wheels.

Chapter 20

HONING, SUPER-FINISHING AND LAPPING

Honing is akin to grinding in that it uses the same abrasives held by the same bonding materials, but otherwise it is very different. In honing a surface a block of bonded abrasive is pressed against the surface with a more or less constant force and the block is then slid to and fro at a comparatively slow speed. The action is a cutting one, the abrasive particles taking minute cuts very much as in grinding, but the amount of metal removed is generally quite small and the process is essentially one for eliminating local irregularities of the surfaces operated on rather than shaping the surface as a whole. Honing was first applied, in machine shops, to the finishing of internal combustion engine cylinders and is still mainly used for internal cylindrical work although it is also used for external work.

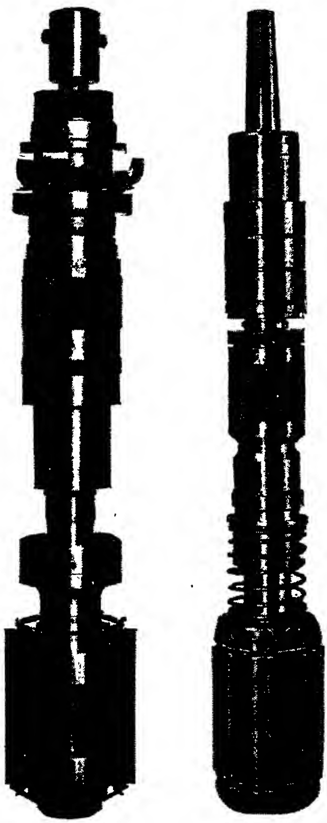


FIG. 305.

Two typical hones are illustrated in Fig. 305 and a honing machine in Fig. 306. They consist essentially of a body member provided with a number of slots in which the stone-carriers are free to slide radially. The stone-carriers can be pressed outwards by two conical portions of a shaft situated inside the body and operated from the upper end of the hone by mechanical or hydraulic means. The stone-carriers are held against the regulating cones by coil spring circlips. The hone body is connected to the spindle of the honing machine by means of two universal joints so that the hone is not constrained, except as regards rotation, by the spindle but is positioned and guided entirely by the hole being honed. The hone is rotated at a speed which, during any particular operation, is constant and is reciprocated in and out of the hole at a constant number of strokes per minute. The stroke is such that about one-third of the length of the hone stones emerges at each end of the hole. When a blind hole is being honed the machine can be set to provide a dwell while the hone

is at the bottom of the hole. During honing the stones are flooded with a lubricant, usually paraffin. As a general practice the operation is carried on for a definite time which is established by trial.

The honing process is not really suitable for correcting the shape of a hole although it will gradually reduce the errors in circularity and, more rapidly, that of taper; hence it is important that the work should be rough machined to fairly close limits, the honing being used to produce the final surface finish only. The amount of stock generally removed is

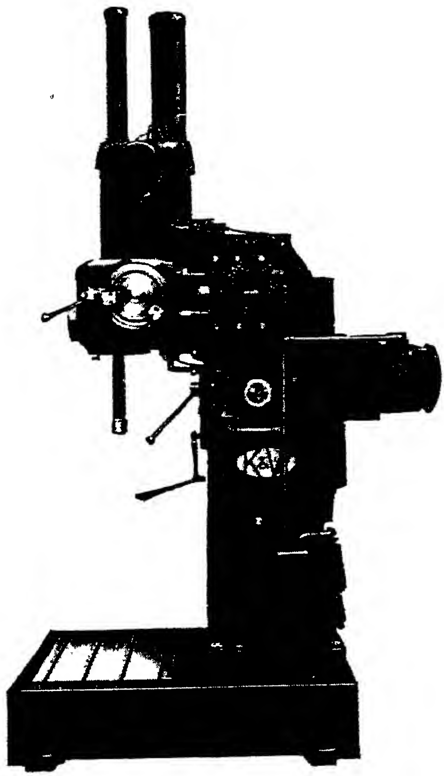


FIG. 306.

about 0·0005–0·005 in. The speed of rotation is such that the surface speed of the hone is from 200 to 300 ft. per minute, while the axial movement is at an average speed of about 70 ft. per minute. As has been pointed out in the previous chapter the chief advantages of honing over internal grinding are that the accuracy attainable does not depend appreciably on the depth of the hole and, secondly, the time required to remove a given amount of stock and to produce a given finish is less.

Super-Finishing. This name has been given to a process for finishing the surfaces of parts which was developed at the Chrysler motor-car factory in America some years ago. It has been described by D. A. Wallace in *Trans. S.A.E.*, February, 1940, from which paper much of the following information is taken. The process consists essentially of rubbing very fine grit abrasive stones over the surface of the work under very light pressures and with a flood of lubricant, while the stone is given a rapid oscillation of small amplitude (about $\frac{3}{16}$ in.) at right angles to the direction of motion of the work.

Silicon carbide has been found to be the best abrasive for use on cast iron, and aluminium oxide for steels. The grits used are 320, 400, 500, 600 and 1,000. The bond used is the vitrified bond and, as in grinding, the harder the steel the softer the bond used, but even on soft steels the bond is only a medium one. The pressure between the stones and the work ranges up to about 20 lb. per sq. in.

The work speed ranges from 15 to 40 ft. per minute for the early roughing stages and from 50 to 100 ft. per minute for finishing; parts are, however, commonly finished in a single operation and the work speed then ranges from 40 to 70 ft. per minute. For short parts, not exceeding about 2–3 in. in length, the stones are made as long as the part and receive only the oscillatory motion ; for longer parts a longitudinal traverse is superimposed on the oscillatory motion. This traverse is at the rate of $\frac{1}{16}$–$\frac{3}{8}$ in. per revolution of the work.

The amount of stock removed during the process varies from 0·0001 to 0·0020 in. and depends chiefly on the degree of finish left by the previous operation.

The time taken for superfinishing a surface depends of course, on the finish required and the finish left by the previous operation. It depends also on the length of the part. For short ground parts the time is of the order of 10–60 seconds.

The measurement of the smoothness or roughness of surfaces is a matter that has only come to be considered in recent years and the methods used cannot be described here, but it will be found that although different methods and instruments give somewhat different results a given instrument can give consistent results and can grade a number of surfaces in order of increasing smoothness. In the *Profilometer* the unit in which the reading is obtained has been named a " micro-inch " ; it is actually an arbitrary unit. Using a profilometer the following readings are typical of various surfaces :

Surface finish	*Profilometer readings*
Rough turned	100–200
Finish turned	50–100
Rough ground	15–50
Finish ground	10–25
Honed	2–8
Lapped	2–12
Superfinished	2–10

The Advantages of Superfinishing. The principal claim made for superfinishing is that it greatly reduces the initial wear of mating parts where motion occurs; a secondary claim is that it reduces the friction between the parts. Undoubtedly these claims are justified and, since the process is not at all costly, it will undoubtedly become widely used. Another advantage is that localised annealing of hardened bodies brought about by overheating during grinding is shown up, the annealed spots appearing greyer than the unannealed parts.

The reason why a superfinished surface wears less than others is thought to be partly, if not wholly, due to the metallurgical condition of the surface layers and Fig. 307, which is taken from D. A. Wallace's

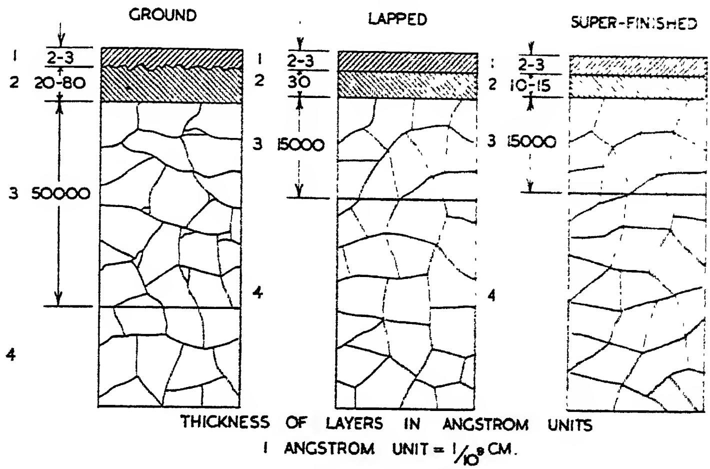


Fig. 307.

paper, previously mentioned, shows the difference between ground, lapped, and superfinished surfaces.

The chief differences between the ground and superfinished surfaces are seen to be (*a*) a great reduction in the thickness of the layer 2 (Fig. 307) of loose fragments, (*b*) a great reduction in the thickness of the layer 3 of strained crystals, (*c*) the elimination of any overheating of the strained crystals, and (*d*) the absence of any trapped abrasive.

Lapping. This is a process by means of which two surfaces are made to conform, the one to the other, as closely as is possible of achievement by any means. Briefly it consists in rubbing the surfaces together, with a very thin layer of very fine abrasive between them, until the surface irregularities are removed and the two surfaces fit closely. Lapping is also used for only one surface of a mating pair, for example the shaft and not the bearing brass, but in this case the place of the mating body is taken by a separate *lap* and the lapping process makes the surfaces of

the lap and shaft conform and brings each of them to cylindricality. This is, perhaps, the commonest form of lapping and it will now be described.

Laps are made of various materials but cast iron is most commonly used; wood is fairly common and steel, brass, and lead rather less common. An external lap is shown in Fig. 308. It is split by a saw cut and can be closed in by tightening one or more screws A. The diameter of the hole D is made the same as that of the piece to be lapped and the hole is, of course, bored before the saw cut is made. Internal laps are made to expand, various means being used to achieve this result; as the amount of adjustment required is very small indeed quite primitive expanding devices will serve.

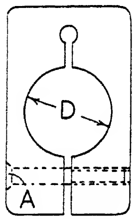


FIG. 308.

The abrasives used are silicon carbide and aluminium oxide in flour form, natural-emery flour, diamond dust, rouge (ferric oxide, Fe_2O_3), green rouge (chromium oxide, Cr_2O_3), boron carbide B_4C, and crocus powder. Lapping usually starts with a comparatively coarse emery flour, is continued with finer flours, and is finished with rouge or crocus powder. The abrasives are used in the form of a paste, oil, paraffin, or water being used for the binding medium and the consistency being usually that of thick cream. The abrasive paste is put on to the work or lap by hand or by coating a flat plate and rolling the work or lap on it. External laps can be charged by rolling a bar (smaller in diameter than the lap) on a charged surface plate and then rolling it inside the hole of the lap. The lap is then transferred to the work and is closed down until it can be moved only by a light effort. It is then moved to and fro over the work with a kind of figure of eight movement. After this has gone on for about 10–20 seconds the lap is rotated slightly to a new position and the motion restarted. The process is continued, with new changes of the abrasive paste at intervals, until the surface approaches the required size; the abrasive is then changed for the finer grades so as to improve the surface finish until finally the work is brought to the required size and is left with the desired surface finish. The process may take anything from a few minutes up to several days.

Lapping should be distinguished from polishing. The surface left by lapping does not usually have a bright shiny appearance but a matt one, whereas the essence of polishing is to produce a shiny surface. Lapping definitely removes metal from the lapped surface although the amount may be only a few ten-thousandths of an inch, whereas polishing does not as a rule remove any appreciable amount of metal. Lapping improves the geometrical shape of the body lapped both generally and locally, whereas polishing does not. Lapping is essentially a cutting process, while polishing consists of producing a kind of plastic flow of the surface crystals so that the high spots are made to fill the low spots.

When lapping the ends of slip or block gauges and measuring rods it is necessary to use some device to enable the lapped surface to be kept square with the axis of the block or rod ; Fig. 309 shows such a device.

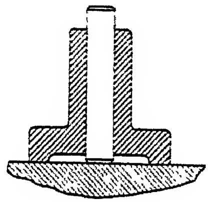


FIG. 309.

Machine Lapping. Lapping by hand is too slow to be used much commercially and is confined to the manufacture of gauges and special equipment. Lapping has, however, been converted from a purely hand operation to one which is partly or wholly a machine operation. In the lapping of the plungers and barrels of diesel-engine fuel-injection pumps, for example, the lap is continuously rotated by power and the hand is used merely to move the plunger or barrel to and fro axially. In this

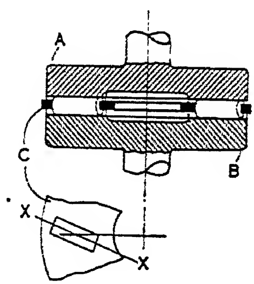


FIG. 310.

way the time required for lapping is reduced to a matter of minutes instead of hours and the plungers are obtained accurate to $\pm 0{\cdot}00005$ in. Gudgeon pins for internal combustion engines are now lapped by a purely machine process. A number of pins are placed between two plates, A and B in Fig. 310, whose surfaces have previously been lapped flat. The pins are placed in slots in a holder C so that their axes XX are not quite radial. The plates A and B are rotated and the holder C is given an oscillation of about 1 in. amplitude. A stream of paraffin in which fine abrasive flour is suspended is fed to the centre of the plates and flows outwards and the pins are thus gradually lapped to size.

Chapter 21

METHODS OF MEASURING. MEASURING INSTRUMENTS AND GAUGES. LIMIT GAUGING

The methods used for making measurements in machine shops and gauge rooms are very diversified, ranging from the use of ordinary steel rules to the use of extremely accurate measuring machines. The increasing complexity of modern mechanisms and the advances made in their loading have resulted in the allowances and tolerances allotted being gradually reduced until they are only a fraction of what they were ten years ago. This in turn has made the necessity for accurate measurement greater than ever and methods which were once used only in metrological laboratories are now in common use in gauge rooms. The method to be adopted for making any particular measurement depends primarily on the accuracy required and an attempt has been made in Table I below to give an indication of the order of accuracy possible with various methods of measurement.

In order to fix our ideas let us consider a specific measurement, namely, the diameter of a cylindrical plug about 1 in. in diameter.

The principal methods available are listed below :

1. Graduated scales and tapes.
2. Callipers set to graduated scale.
3. Callipers set to a plug gauge.
4. Sliding vernier callipers.
5. External micrometer used direct.
6. External micrometer set to plug or block gauge.
7. Dial indicator or other magnifying instrument.
8. Measuring machine using graduated scale.
9. Comparator.

The use of a graduated scale is only practicable if the end of the plug is square with the axis of the plug and if the corners are sharp, and this method is obviously not susceptible of very great accuracy. Similarly the use of a graduated tape would be absurd for making this measurement but if the diameter were, say, 10 or 20 in. or more the graduated tape might be the best method, the circumference being measured and the diameter then calculated ; special tapes with suitable end fittings can be obtained for this purpose. A correction for the thickness of the tape might be necessary.

In the second method a pair of callipers is adjusted to just pass over the plug and then is laid on an ordinary steel rule so that the setting can be read off ; the simplest way is to set one leg against the end of the

rule and to read off the graduation opposite the other leg. The errors involved in this kind of measurement are of two main kinds: firstly, those due to the varying tightness of the calliper setting to the plug and, secondly, those made in reading the calliper setting against the rule; the second errors will generally be the larger.

In the third method the callipers are set to the plug and are then tried on standard plug gauges until one is found which gives the same "feel." Generally, however, this method is used the other way round so as to enable the work to be made equal in size to a given plug gauge. Here

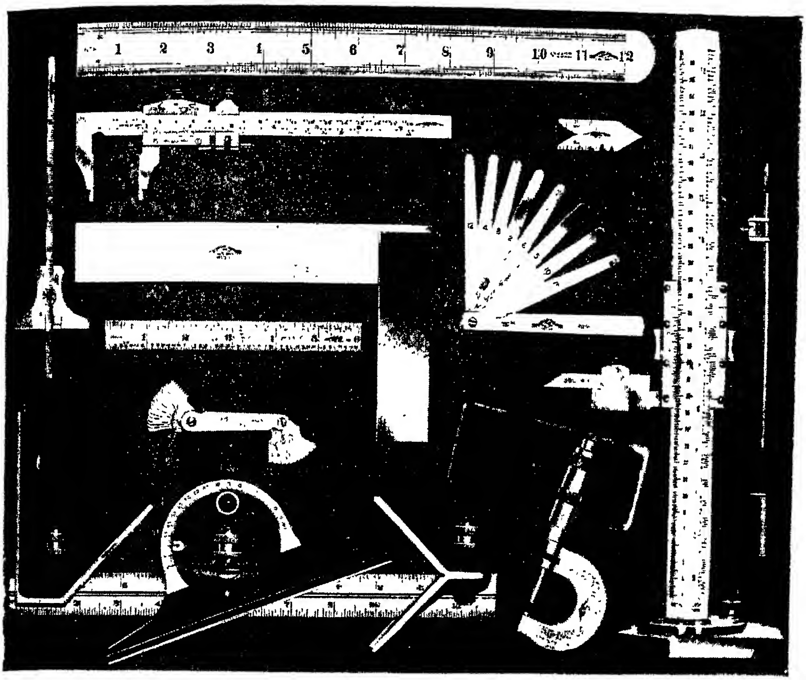


FIG. 311.

the errors may be due to differences in the feel of the callipers on the gauge and work and, also, of course, errors in the gauge itself. With practice the feel of the callipers can be made very closely the same on both work and gauge and the method is much superior to the previous one.

A pair of sliding vernier callipers is shown in Fig. 311 (2nd from top). They are provided with a vernier by means of which readings to 0·001 in. may be obtained. Sliding callipers are not very suitable for measuring cylindrical work because the "feel" of these instruments is not very delicate and errors may arise through the straining of the jaws. Another

source of error is the tilting of the sliding jaw, and a third is displacement of the zero ; the latter can be eliminated by observing the reading when the jaws are closed. Sliding callipers, when fitted with a suitable fixed jaw so that they will stand on a surface plate and when provided with a scribing point as shown on the right in Fig. 311, are extremely useful for marking out purposes. Vernier sliding callipers violate the " principle of alignment " which, briefly, states that the scale ought to be made to coincide with the dimension being measured or, if that is not practicable, and it is not usually practicable, it should be placed in the same straight line as the dimension. British Standard Specification No. 887—1940 deals with vernier callipers.

An ordinary external micrometer is shown in Fig. 312 ; it is probably the most widely used measuring instrument of any. Most micrometers are graduated to read thousandths of an inch, the barrel or thimble being graduated with twenty-five divisions and the micrometer screw having forty threads per inch. The graduations on the sleeve are therefore tenths of an inch divided into four. By adding vernier lines to the sleeve the readings may be taken off to 0·0001 in., but the accuracy of measurement is seldom as good as that. The errors in measurements made by micrometers are due (*a*) to a zero error being present—this is easily checked and allowed for ; (*b*) to the pressure of the micrometer on the work being excessive ; (*c*) to the spindle being bent or the anvil being out of square ; and (*d*) to errors in the micrometer screw thread and graduations. Attempts have been made to eliminate the errors due to varying pressure by providing some form of friction or spring drive to the thimble, but these attempts have not been very successful. This source of error is, however, largely eliminated in the Zeiss indicating micrometer ; here the anvil is not fixed to the frame but can move slightly and its movement is communicated, after magnification by a lever system, to the indicating pointer ; by making the indicator pointer always coincide with the same graduation the anvil pressure can be maintained approximately constant. Alternatively the indicator pointer can be used to show the variations in size of a number of pieces all of which are nominally the same ; for this purpose the micrometer spindle is locked. A micrometer can also be used merely to compare the work with a gauge and in this way all errors except those due to variation in " feel " and, of course, errors in the gauge, may be eliminated.

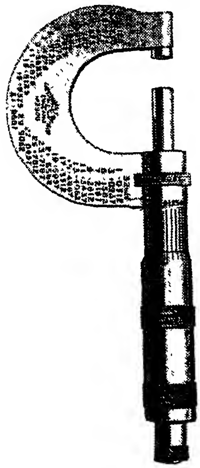


FIG. 312.

Next to the ordinary micrometer the most widely used measuring instrument is, probably, the *dial indicator* or *clock gauge*, commonly

referred to as "the clock." An example is shown in Fig. 313. It consists essentially of a plunger which can slide in a guide in the body of the instrument and whose motion is transmitted through a magnifying mechanism to the indicating pointer. The degree of magnification varies but in the most commonly used instruments the dial has 100 graduations and each one represents a plunger movement of either 0·001 or 0·0001 in. The dial may be graduated from 0 round to 100 clockwise or from 0 to 50 both ways. The dial is movable so that it can easily be set to zero and is sometimes provided with a clamping device. The total plunger movement varies with the type of magnifying mechanism and the degree of magnification and may be as little as 0·05 in. and as great as 0·5 in. The magnifying mechanisms used are roughly divisible into two kinds, rack and pinion mechanisms and lever and toothed arc mechanisms, and these are indicated diagrammatically in Fig. 314. The first type usually permits of a greater total plunger motion. The accuracy of dial indicators depends on many factors, the primary ones being the accuracy of cutting of the rack and pinion teeth and the elimination of the effects of backlash. Secondary causes of error are inaccuracy in the graduation of the dial, eccentricity of pointer and dial, and excessive friction.

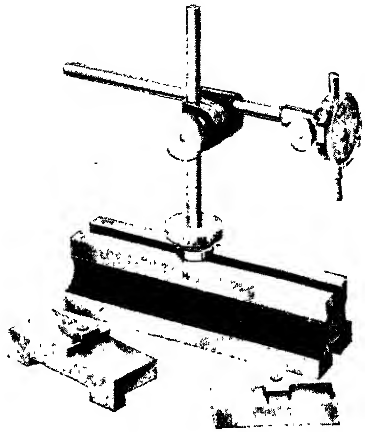


FIG. 313.

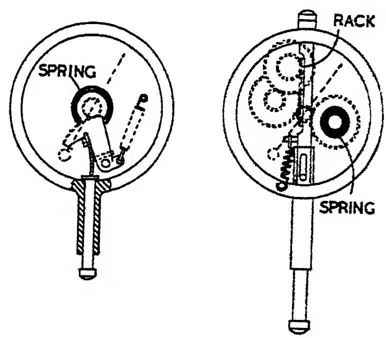


FIG. 314.

The dial indicator cannot be used by itself but needs certain accessories and it is not, strictly, a measuring instrument at all but only a means of comparing a piece of work with a gauge. When used for gauging purposes the indicator is mounted on some kind of a stand having a suitable platform or table on which the work to be gauged can rest and is adjusted so that a gauge, equal in size to the work being gauged, produces a suitable spindle movement; the indicator dial is set to zero with this gauge in position. The work is then gauged by passing it beneath the indicator and observing the pointer readings. The opera-

tion is greatly facilitated if the indicator dial is fitted with two adjustable pointers to mark the upper and lower limits for the work piece.

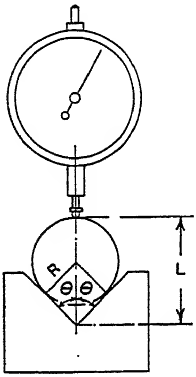


Fig. 315.

When measuring cylindrical work it is often most convenient to place the work on a V-block which is fixed relatively to the dial indicator as in Fig. 315. This increases slightly the sensitivity of the indicator. Thus, $L=R\frac{(\sin\theta+1)}{\sin\theta}$, and if R increases to $R+\delta R$ then L increases to $L+\delta L=(R+\delta R)\ \frac{(\sin\theta+1)}{\sin\theta}$ so that $\delta L=\delta R\frac{(\sin\theta+1)}{\sin\theta}$; and if $\theta=45$ degrees, $\delta L=2{\cdot}4\delta R$ approximately, whereas if the work had rested on a flat support, δL would have been equal to $2\delta R$. If θ is made 30 degrees, then $\delta L=3{\cdot}0\delta R$.

In the Krupp " Mikrotast " gauges the magnifying indicator is combined with a V-support piece as indicated in Fig. 316. It is easily seen that $\delta L=\delta R\frac{(1-\sin\theta)}{\sin\theta}$.

Dial indicators are widely used for setting work in machines. In a lathe, for example, work may be set true by clamping the dial indicator to, say, the tool post, adjusting it so that the spindle bears on the work and then adjusting the work until the indicator reading does not vary as the work is rotated. In a milling machine the edge of a piece of work may be set parallel to the work-table traverse by mounting a dial indicator on any convenient fixed part of the machine, arranging the indicator spindle to bear on the work edge and then adjusting the work until the indicator reading remains constant when the work table is traversed to and fro. In a boring machine the face of a piece of work may be set perpendicular to the spindle axis by clamping a dial indicator to an arm fixed to the spindle, adjusting it so as to bear on the face of the work, and then rotating spindle, arm, and indicator all together, the work being adjusted until the indicator reading is constant.

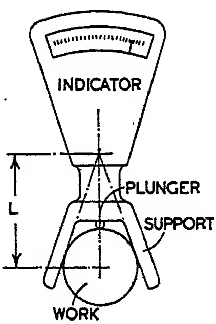


Fig. 316.

It will be seen that the dial indicator is a most useful and versatile instrument.

It may be noted that most dial indicators will repeat a given reading with a greater degree of accuracy than they will indicate a variation by a change of scale reading. This is because in the former operation errors due only to backlash and excessive friction enter into the result whereas when the scale reading varies other errors, such as those due to the cut-

ting of the rack teeth and the eccentricity of the scale and pointer axis, also come in.

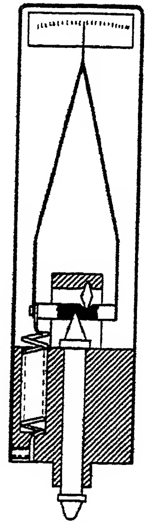


Fig. 317.

Other Magnifying Indicators. The gradual but steady increase in the accuracy demanded of the machine shop has produced a demand for indicators of greater sensitivity than the ordinary dial indicator and many different types have been developed during the last twenty years or so. A few of these will be briefly described.

The *Hirth minimeter* was one of the earliest instruments having an accuracy higher than that of ordinary dial indicators. It used a purely mechanical magnifying system which is shown, diagrammatically, in Fig. 317. It is made with various sensitivities, scale graduations of 0·001, 0·00025, 0·0001, and 0·00005 in. being available.

Fig. 318 illustrates the " Optical Comparator " made by Messrs. Cooke, Troughton and Simms of York, England. It uses an optical magnifying system; movement of the plunger tilts a small mirror and this deflects a beam of light so that the image of a cross-wire is moved over the scale and indicates the plunger movement. The scale readings in the instrument shown are 0·0001 in., the magnification being approximately 1,000.

Messrs. Optical Machine Tools, Ltd. of Slough, manufacture an

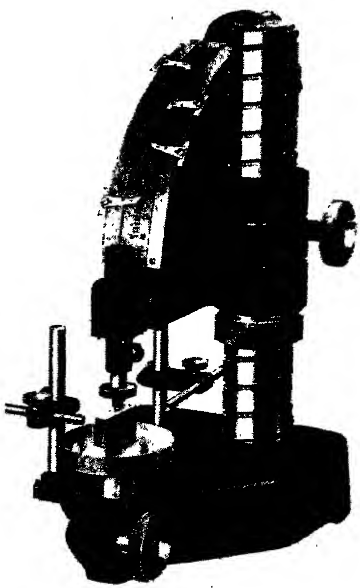


Fig. 318.

indicator having scale graduations of 0·00005 in. and guarantee it to ±0·00001 in.; the "Ultra-Optimeter" made by Messrs. Zeiss has 0·00001 in. graduations and is accurate to 0·0000025 in., while the Zeiss "Interference comparator" has an accuracy of 0·0000005 in. These last three instruments are for gauge room use and necessitate a temperature controlled room if their inherent accuracy is to be fully utilised; the problem of temperature variation is considered later on in this chapter.

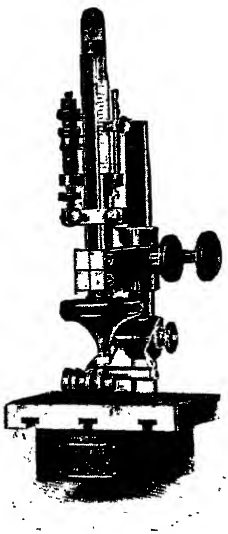


FIG. 319.

Fluid Gauges. The Prestwich fluid gauge, shown in Fig. 319, has its upper anvil carried by a flexible diaphragm which forms the wall of a chamber filled with fluid. A capillary tube communicates with the chamber and movement of the anvil is shown, greatly magnified, by the movement of the column of fluid in the tube. A bracket, seen on the left, carries three pointers, the upper two of which define the limits for the work being gauged while the bottom one should, normally, coincide with the top of the fluid column when the upper anvil is free. If, because of a temperature rise, the fluid expands then the bracket carrying the pointers is merely moved up slightly until the bottom pointer again coincides with the fluid column when the anvil is free. The gauge is set by means of block gauges equal to the smallest and largest permissible work. Its scale graduations represent 0·0001 in. approximately.

The Solex Pneumatic Gauge. The principle of this gauge is as follows. Suppose that air under a constant pressure P_1 is supplied to a closed chamber through a small hole or jet J, as indicated in Fig. 320, and escapes to the atmosphere, pressure P_3, through a second jet K. Then the pressure P_2 will settle down to some value intermediate between P_1 and P_3 and this value, P_2, will depend on the relative sizes of the jets J and K. This will easily be seen when it is realised that the same quantity of air passes through each jet per minute and that this quantity depends on the difference in pressure at the two sides of the jets and, of course, on the size of the jets. Hence if the size of the jet J is fixed while the of the jet K varies, then the corresponding variation of the pressure P_2 could be used to indicate the variation in the size of the jet K.

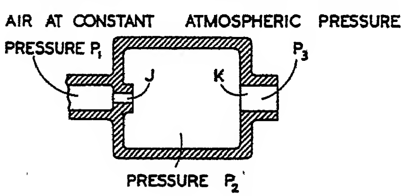


FIG. 320.

Fig. 321 indicates one application of this principle to the gauging of machined parts. The second jet K is now formed by the gap K between the top of the plunger Q and the end of the boss B, the hole H being made so large in relation to J and K that the pressure drop across it is negligible. Clearly variation in the size of the work varies the size of the jet K.

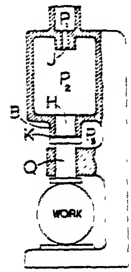


FIG. 321.

Fig. 322 shows, diagrammatically, the complete equipment as applied to the measurement of motor engine cylinders. It consists essentially of the pressure regulator A, the intermediate chamber B, and the gauge plug G. The supply of air to the pipe D is regulated by a valve until there is a continuous small escape from the bottom of the tube E, and in this way the pressure P_1 is maintained constant, its value depending on the dimension H. The outlet "jet" is now formed by the clearances between the faces of the bosses L, L and the surface of the cylinder being gauged. The pressure P_2 in the intermediate chamber B is indicated by the reading h on the gauge tube F. The gauge plug is connected to the intermediate chamber, which is combined with the pressure regulator, by several feet of flexible tubing. The magnifications obtainable may be as high as 20,000.

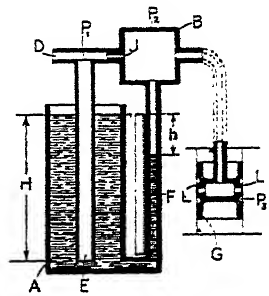


FIG. 322.

Electrical Gauges. Electrical methods of magnification are used in the Pratt and Whitney "Electrolimit" gauges. In these the anvil movement displaces an armature, of magnetic material, which lies between the pole pieces of two inductances and this upsets the balance of an alternating current bridge-circuit of which the inductances are part; the resulting out of balance current is rectified and passed through an ammeter whose scale is suitably graduated so as to record the anvil movement. The instrument is made with various magnifications (this depending principally on the magnitude of the air gaps between the armature and the pole pieces of the inductances) and the scale readings may be 0·0001 or 0·00001 or 0·000005 in. An advantage of this instrument is that the indicating unit may be placed at a considerable distance from the measuring unit; disadvantages are that it takes some 15 minutes to reach its working temperature, and necessitates a suitable power supply.

Measuring Machines. These may be divided into two groups: (*a*) those in which the measurement is read directly off a graduated scale and which may be called *scale-type* machines, and (*b*) those in which a fixed gauge of some kind is compared with the piece being measured;

this type may be called the *comparator type*. An example of the first type is shown in Fig. 323. It consists essentially of a heavy bed A at one end of which is a fixed anvil B and whose upper surface is accurately machined to form ways upon which the saddles C and D can slide. The saddle C carries a cross-sliding support E which is free to slide relative to C and perpendicular to the main bed ways. The saddle or carriage D is provided with an anvil F, the standard scale, and a pressure or contact indicator. The standard scale cannot be seen in the illustration but is housed inside the carriage; it is visible through a window G and

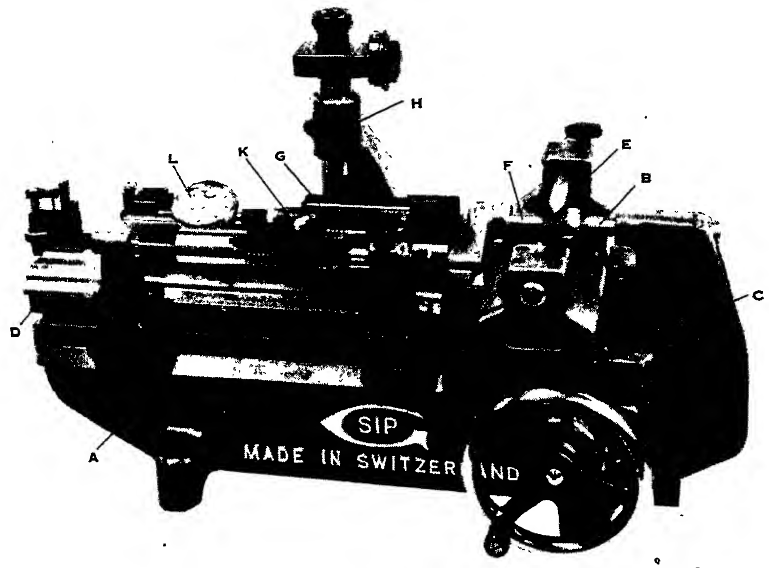


FIG. 323.

can be read by means of the microscope H which is fixed to the bed. The contact indicator serves to keep the anvil pressure constant at 1 lb. The standard scale is graduated with 0·45 in. divisions (or in millimetres) and these are subdivided by the micrometer eye-piece of the microscope. An enlarged view of this is given in Fig. 324; the scale K is moved by a micrometer screw and knurled wheel M until the double index lines O straddle one of the standard scale lines L and the reading of the pointer on the scale K, and the reading of the micrometer dial, are observed. The micrometer dial readings are 0·00005 in. and the divisions of the scale K represent 0·005 in. A calibration chart appertaining to the particular scale fitted to each machine is supplied and enables measurements to be made to 0·00001 in. For

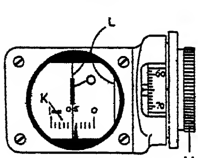


FIG. 324.

measuring the pitch of a screw the ball-ended feeler K is used in conjunction with the indicator L. The jaws seen at the extreme left of the machine enable internal measurements to be made.

The comparator type of measuring machine is similar in general appearance to the scale type; the movable anvil actuates a contact indicator and this motion is used to measure the difference between the work being measured and a gauge of known, and approximately equal, length which is substituted for the work after the measuring carriage has been adjusted and the contact indicator reading noted. The accuracy attainable depends principally on the accuracy of the contact indicator and its scale since, as will be seen later, the gauges can be obtained accurate to ±0·0000025–0·00001 in. according to their length. If the contact reading is made the same on both readings, by selecting a gauge exactly equal to the work, the accuracy attainable will be slightly better than if the contact indicator scale readings are different.

TABLE 1

ORDERS OF ACCURACY IN MEASUREMENT

Callipers set to a foot-rule	±0·01
Callipers set to a plug gauge	±0·0025
Sliding vernier callipers	±0·001
External micrometer used direct	±0·0005
External micrometer set to slip gauge	±0·0002
Dial indicator using its scale	±0·0001–0·0008
Dial indicator using " null " method	±0·00005–0·0002
Solex pneumatic gauge	±0·0001
Zeiss " optotest "	±0·00004
Zeiss " optimeter "	±0·00001
Zeiss " ultra-optimeter "	±0·0000025
Zeiss measuring machine (on 2 in.)	±0·00003
Zeiss " interference comparator "	±0·0000005
Ordinary dividing head	±2–3 mins.
Optical dividing heads	±20 secs.
Angular measurements with " sine bar "	±5 secs.
" Slip gauges," guaranteed to	±0·000001–0·0000025

The above table is intended to give only a general ideal of the order of accuracy attainable in the measurement of a block about 1 in. in size. Cylindrical objects cannot be measured in measuring machines to such a high degree of accuracy as rectangular objects and internal cylindrical measurements are still less accurate.

The Level Comparator. This instrument, which is illustrated in Fig. 325, enables the lengths of two pieces to be compared with a very high order of accuracy. It consists essentially of a rotatable platform A, Fig. 326, whose upper and lower surfaces have been lapped accurately parallel, and of a spirit level B provided with two ball feet a short distance apart. The column and bracket, in Fig. 325, serve to support the level B only when it is not resting on its feet. The principle involved is indicated in Fig. 326. The level is placed with one foot on a gauge X and the other on a second gauge Y and the bubble reading is observed. The level is then

raised clear of both gauges and the table A is rotated half a turn. The level is then lowered on to the gauges again and the bubble reading again observed. The difference in length of the gauges can then be computed provided the distance L, between the contact points of the feet, and the radius of curvature of the level bubble tube, are known. Calling the

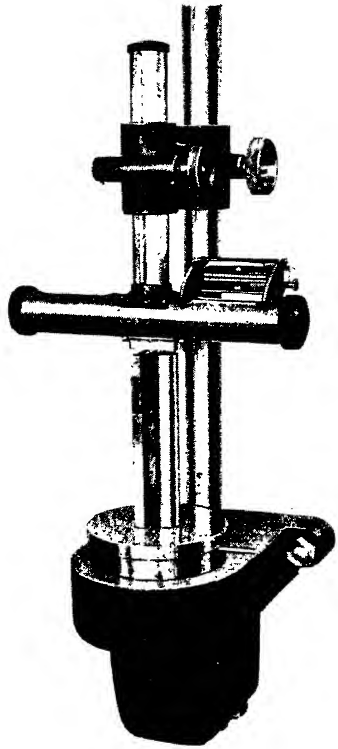


FIG. 325.

lengths of the gauges respectively X and Y and denoting the bubble movement by a,

then $$\sin \alpha = \frac{X-Y}{L}$$

and since α is very small indeed, $\sin \alpha = \alpha$.

Also $$a = R \times 2\alpha$$

$$\therefore \quad \frac{a}{2R} = \frac{X-Y}{L}$$

$$X - Y = \frac{aL}{2R}.$$

Actually the level bubble tube is not graduated at all but the bubble position is read off against a separate graduated scale by means of a half-silvered mirror which enables the scale and the reflection of the bubble to be seen simultaneously. The scale is graduated so that the difference X—Y is given by

$$X - Y = \frac{\text{difference in bubble readings}}{2} \times \frac{1}{F}$$

where F is a factor which depends on L and R, but which is commonly 100,000. Because the magnification provided is very great the range of the instrument is correspondingly small, the maximum difference that can be measured being 0·0001 in. Gauges that differ by more than this

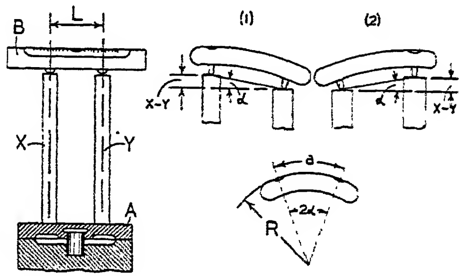


FIG. 326.

amount can be compared by wringing block gauges to them so as to reduce the difference to less than 0·0001.

For descriptions of other comparators the reader is referred to F. H. Rolt's comprehensive book " Gauges and Fine Measurements."

Temperature Control. In what has been said above no mention has been made of temperature effects, but it is obvious that as the order of accuracy of measurement is increased so the effects of variation of temperature become more and more important. The coefficient of expansion of steel is about 0·00001 per degree Centigrade so that a variation in temperature of 1 degree will produce, in a 10-in. gauge, an alteration in length of 0·0001 in. However, since the work being measured generally has a coefficient of expansion not very different from that of gauge steel the temperature does not usually have to be taken into account until measurements are made to a higher degree of accuracy than 0·0001 in. It is important, however, that the work and measuring instrument should be at approximately the same temperature. When measurements are being made to less than 0·0001 in. the operation should be carried out in a temperature controlled room and the work should be brought into the room a sufficient time before making the measurement to ensure its being at the room temperature. The temperature at which

gauges, etc., are, by agreement, standardised is 62° F., or $16\frac{2}{3}$° C., and gauge rooms are commonly maintained at that temperature by thermostatically controlled heaters ; this temperature is called the "temperature of adjustment." By international agreement the materials used for the scales of measuring instruments are required to have a coefficient of expansion of 0·000015 per degree Centigrade. The more sensitive measuring instruments are generally shielded from the heat of the operator's body by means of sheets of special non-conducting glass.

Standards of Length. The measurements made in any country must be in terms of some standard laid down by the laws of the country. This standard, the *Primary standard*, must obviously be kept very carefully and cannot be used at frequent intervals, consequently copies of it are made ; these are called *Secondary standards* ; they are compared at rare intervals with the Primary standard and are used only for comparison with the *Tertiary standards*. The latter, of which there are quite a number, are kept at laboratories which are authorised to undertake the checking of gauges, etc., and to issue certificates of measurement. The Tertiary standards are used, at comparatively frequent intervals, to check the *Working standards* in everyday use in the metrological laboratory.

A somewhat similar system, but much less elaborate, is used in engineering shops. The workmen's gauges are in daily use and are checked against reference gauges at intervals ranging from daily to monthly. The reference gauges in turn are checked at longer intervals usually by means of standard *block* or *slip gauges* but sometimes by direct measurement on a measuring machine. The block gauges are usually the ultimate standard so far as an engineering works goes.

Block or Slip Gauges. A set of block gauges is shown in Fig. 327. They are rectangular blocks of steel, hardened, ground, and lapped so that their ends are optically flat, parallel, and spaced apart by the amount engraved on the face of the block (on the ends in the smaller sizes), to a high degree of accuracy. Such gauges were first made by Johansson, in Sweden, and are sometimes referred to as Johansson gauges. During the 1914–18 war a method was developed at the National Physical Laboratory, Teddington, by which the time and cost of manufacture were much reduced. Such gauges are now marketed by a number of firms. They can be "wrung" together by holding them one in each hand, bringing their ends into

Fig. 327.

contact and then twisting them to and fro while applying a slight end pressure. Hence a composite gauge of any desired length, within the range of the set, can be built up and the accuracy of the combination will not be appreciably different from that of the individual blocks. The adhering of one block to another has been shown to depend on the presence of a film of moisture or grease between them; chemically clean blocks cannot be wrung together. Blocks should always be carefully wiped before wringing and a chamois leather is generally used.

The sets commonly used in workshops enable any dimension up to about 12 in. to be built up, the minimum step being 0·0001 in. They are now obtainable in several different qualities; the highest quality blocks are guaranteed to be accurate to within $\pm 0{\cdot}000002$ in. per inch,

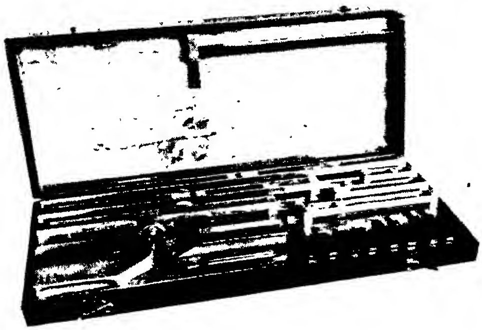


FIG. 328.

while the second and third qualities have errors of two and four times that amount respectively.

Accessories are also obtainable which facilitate the use of the gauges; these are shown in Fig. 328. Thus for measuring holes, blocks which are longer than the ordinary blocks and which are suitably rounded on one side as seen at the right-hand bottom corner in Fig. 328, can be clamped in a special clamp with a pile of blocks between them thereby producing the equivalent of a sliding calliper gauge. A scribing point (6th from right in Fig. 328), in conjunction with a suitable fixture (bottom left, Fig. 328), produces the equivalent of a scribing block for marking out purposes. Blocks formed with conical points as shown (8th from right in Fig. 328) are also useful.

The wear produced by wringing the blocks together is very small indeed. In a test made at the National Physical Laboratory and quoted by Rolt sets of eight 0·25-in. blocks were wrung together 200 times and their combined length was measured after each wringing. It was found that the average wear *per block* after the 200 wringings was about two-millionths of an inch for the set finished with an extra fine finish and

four-millionths for the set having a comparatively coarse finish. In the finely finished set the wear occurred chiefly during the first 100 wringings, the rate of wear thereafter being extremely low—less than the probable errors of measurement. The wear of the "coarsely" finished set was still measurable after the first 100 wringings, the combined length of the eight blocks changing 0·000005 in., approximately, during the second 100 wringings. Chromium-plated block gauges are now on the market, and it is claimed that, for similar usage, they wear only about $\frac{1}{20}$ as much as unplated gauges.

Limit Gauges. A limit gauge is a form of gauge which, *when properly used*, will ensure that any given dimension of a piece of work will lie between two specified amounts, the smaller of which is called the *low limit* and the greater the *high limit*. Fig. 329 shows three forms of limit gauge: the upper one is called a "double-ended snap gauge" and is suitable for checking a male piece of work, the middle gauge is a rather more convenient form of gauge, while the bottom one is a double-ended plug gauge for female work. The dimensions x are greater than the dimensions y and the ends of the double-ended gauges are labelled *Go* and *Not Go* as shown. If the work is such that the *Go* end passes over it and the *Not Go* end will not do so, then it must lie between the limits x and y and it would be accepted. The amount $x-y$ is therefore the amount the workman has "to play with" or, alternatively, it may be regarded as the greatest variation in the dimension of all the parts made that can be tolerated; it is consequently called the *tolerance*.

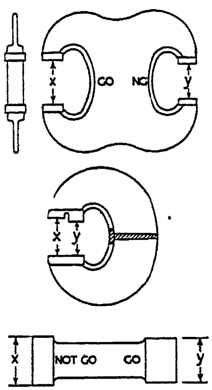


FIG. 329.

A snap gauge cannot be made absolutely rigid and so will pass over a larger piece of work if a heavy pressure is applied to it than if only a light pressure is used. The International Standards Association defines the size of a snap gauge as the size of a disc over which the gauge will just pass under its own weight. In practice the weight of the work is often used by fixing the gauge in a clamp with the jaws uppermost, and applying the work to it.

The Nominal Dimension. This is the size a part is desired to have and from which it will differ only because, for economic reasons, the workman must be allowed a tolerance. The tolerance permitted can, however, be made (*a*) all positive, (*b*) all negative, or (*c*) partly positive and partly negative; when it is all positive or all negative the system is said to be a *unilateral* or one-sided system, whereas a system in which the tolerance is partly positive and partly negative is called a *bilateral* one. Both systems are in use in workshops, but the engineering standards

institutions in most countries recommend that the *unilateral* system should be adopted wherever possible. On a bilateral system a part would be dimensioned on a drawing as x^{+a}_{-b}, while on a unilateral system it would be dimensioned either $y^{+0\cdot0000}_{-c}$ or $z^{-c}_{+0\cdot0000}$. If the actual tolerance is the same in both cases then $c=a+b$. Clearly if the part is required to lie between the same absolute limits, say D_{max} and D_{min}, then $y=D_{max}$, $z=D_{min}$, and $x=D_{max}-a=D_{min}+b$, i.e. $x=y-a=z+b$. It is convenient in a unilateral system to make the nominal dimension correspond with the maximum permissible size for a male part and the minimum permissible size for a female part; this is sometimes referred to as "specifying maximum metal."

The Determination of Tolerances. The question, What should the tolerance be? is one that is difficult to answer and which is settled ultimately by experience. Clearly the greater the tolerance permitted on an article the easier and cheaper it will be to make the article; consequently *it is desirable that the tolerance shall always be as large as possible.* If, however, the tolerances are too large then parts which should mate together will either not do so at all or the fits will be so slack as to upset the working of the mechanism of which the members are parts. In the first case the parts will either have to be rectified by additional machining or will have to be fitted by hand, both of which procedures will increase the costs tremendously. In the second case the mechanism is, in effect, worn out as soon as it is made. Hence there is an upper limit to the tolerances that can be permitted and the present tendency is towards a lowering of this limit; one of the problems confronting production engineers is how to keep production costs down in spite of the steady reduction in tolerances. The permissible tolerance thus depends on the kind of fit that is desired between mating parts and this matter must now be considered.

Qualities of Fit, Allowances. Consider a shaft that is going to work inside a bearing; it is obvious that the diameter of the shaft must be slightly less than that of the bearing or it could not be inserted, but the amount it should be less depends on the conditions in which the assembly will be used. If the clearance between the shaft and bearing were very small the fit of the parts might be described as *close running*, whereas if it were quite large, the fit might be called a *slack* one. Similarly a plug that can only just be pushed into a hole might be said to be a *push* fit in the hole, whereas if the plug were definitely larger than the hole so that it could only be forced in by, say, an hydraulic press, the fit might be called a *force* fit. All these terms are, however, somewhat vague and their meanings are, to some extent, matters of opinion. It is better, therefore, to avoid using them and to specify the kind of fit required by laying

down the maximum and minimum clearances that are permissible. Since in the case of force fits the " clearance " is negative the term *allowance* has been introduced to denote *the difference between the dimensions of two mating parts which is specified in order to obtain the required kind of fit between them.* An allowance may thus be either positive or negative; it is positive when the male part is smaller than the female and negative when the male part is larger than the female. Allowances should be distinguished from tolerances; an allowance concerns *two mating parts,* a tolerance concerns a *single part.* If, however, any one of a number of male parts, for which a definite tolerance is laid down, is mated with any one of a number of female parts, also made to a specified tolerance, then the clearance, or allowance, may vary between an upper and a lower limit as will be seen on examina ion of Fig. 330. At *a* the largest

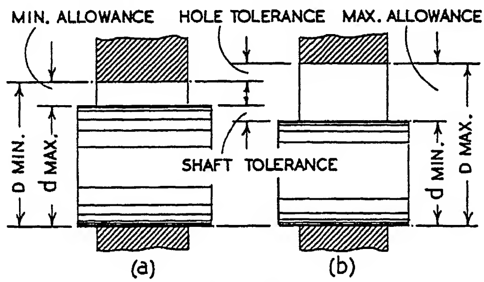


FIG. 330.

permissible shaft, diameter d_{max}, is shown mated with the smallest permissible hole, diameter D_{min}, thus giving the minimum allowance, $D_{min}-d_{max}$. At *b* the smallest shaft is mated with the largest hole, giving the maximum allowance as $D_{max}-d_{min}$.

If the values of the maximum and minimum allowances consisfent with proper functioning are known then the sum of the tolerances permissible on the parts is settled, being given by the difference of those quantities, and it may be split up between the parts as may be found most desirable. Generally, however, the value of the *minimum* allowance consistent with proper functioning is known and may be laid down, but instead of laying down the maximum allowance and deducing the tolerance the tolerances are laid down, thereby determining the maximum allowance. The tolerances permitted vary according to the class of work and will be considered later.

Hole or Shaft Basis. Now suppose that a series of mating shafts and holes are to be made all nominally the same in size but with different qualities of fit, ranging from, say, slack, having an allowance of several thousandths of an inch, to a tight push fit having an allowance of only a few ten-thousandths. The different fits could be obtained in three ways.

Firstly, we could make all the holes the same size (within the permitted tolerance) and could obtain the different fits by varying the nominal sizes of the shafts. The actual sizes of the shafts might then vary from their nominal sizes by the amount of the tolerance. When this is done the system is said to be on a *hole basis*. Secondly, we could do the exact opposite, namely, keep the nominal size of the shafts constant and vary the nominal sizes of the holes. If this is done the system is said to be on a *shaft basis*. Thirdly, we could vary the nominal sizes of both hole and shaft. This method, having nothing to recommend it, will be disregarded.

Both hole and shaft bases are now in use, but for general purposes the hole basis is sometimes regarded as preferable and it is recommended by the British Standards Institute. The International Standards Association (I.S.A.), however, has expressed the opinion that both bases should be used concurrently and that it is not desirable to give either system preference. One of the main arguments in favour of the hole system is that holes are formed, to a large extent, by fixed-size tools such as drills and reamers, whereas shafts are machined on lathes and grinding machines on which it is as easy to work to one dimension as to any other; also that holes are gauged with fixed, as opposed to indicating or adjustable, gauges to a greater extent than shafts. On the other hand, it is sometimes not practicable to adopt the hole basis; shafting, for example, must be a running fit in its bearings but pulleys must be a tight fit on it, and it is impracticable to vary the shaft size from point to point. The question is a controversial one and for a full consideration of the pros and cons the reader is referred to *Proc. I. Mech. E.*, 1920 and 1921.

Standard Tolerances and Allowances. The tolerances that can be permitted thus depend on the allowances, which are determined, ultimately, by experience. In the early years of this century several firms of gauge makers developed systems of tolerances and allowances and manufacturing works also evolved their own systems, and considerable confusion resulted. The British Standards Institute has attempted to reduce this confusion by promulgating a standardised system but has not been completely successful. The B.S.I. system of Limits and Fits is laid down in B.S.I. publication No. 164—1924, and defines the tolerances for four series of holes and fourteen series of shafts. The four series of holes correspond with four grades of workmanship and are denoted by the letters B, U, V, and W. Considering a hole of 1 in. nominal diameter the tolerances are as follows:

Class of workmanship . . .	B	U	V	W
Tolerance in 0·001-in. units .	+0·6 −0	+1·2 −0	+2·4 −0	+4·8 −0

Within each series the tolerances increase with the nominal diameter according to a law of the form $T=a+b\sqrt{D}+cD$ where T=tolerance,

D=nominal size, and a, b, and c are numerical constants. As it is not practicable to have a continuous variation of the tolerance with variation of the nominal size the tolerance is made to go up in a series of steps as indicated in Fig. 331. The positions of the steps are determined by *size multipliers* m, which must be integers, and which may be found, for any nominal diameter D in. by means of the following formula: $m(m-1)>20D \geqq (m-1)(m-2)$. For example, if D=1 in. then $m(m-1)$ must be greater than 20 and $(m-1)(m-2)$ must be less than or equal to 20 ; hence $m=6$ for $6\times5=30>20$ and $5\times4=20$. The actual tolerances

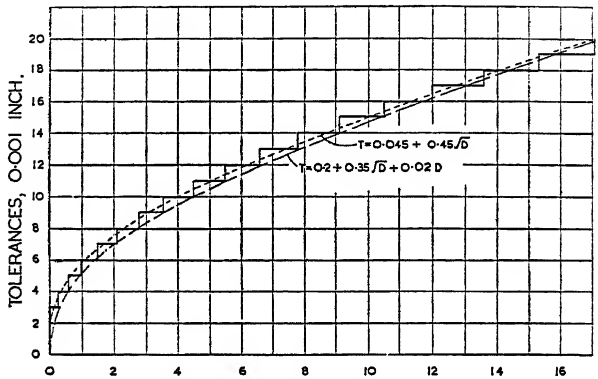


FIG. 331.

are determined by the products of the size multiplier m and *range factor* r whose values depend on the class of workmanship as follows :

Class of workmanship	B	U	V	W
Range factors (uni-lateral holes) .	+0·1 0	+0·2 0	+0·4 0	+0·8 0

The products $m \times r$ give the *deviations* from the nominal size and the algebraic difference of the products gives the tolerance. Thus for the 1 in. diameter shaft, ($m=6$), and B class workmanship, the deviations are $6\times0{\cdot}1=0{\cdot}6$ and $6\times0=0$, the units being 0·001 in. and the limits are 1·0000 and 1·0006.

The B.S.I. system also laid down tolerances for four series of bilateral holes in order to accommodate existing users of bilateral systems. In addition three series of oversize holes were standardised and tolerances were also laid down for non-mating parts. For a full consideration the report quoted should be consulted.

The fourteen series of B.S.I. standard shafts are designated by letters and the tolerances on them, for a nominal diameter of 1 in. are shown in Fig. 332. These tolerances can be calculated in the same manner as for holes and the appropriate range factors are shown in the figure.

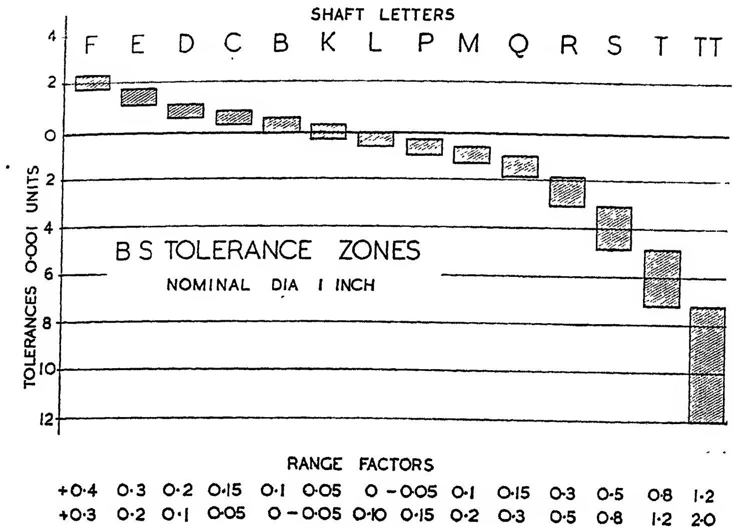


FIG. 332.

Different qualities of fit are obtained by selecting suitable shafts to mate with the holes. The variation of fit obtained by mating the standard shafts with a B class hole is shown in Fig. 333.

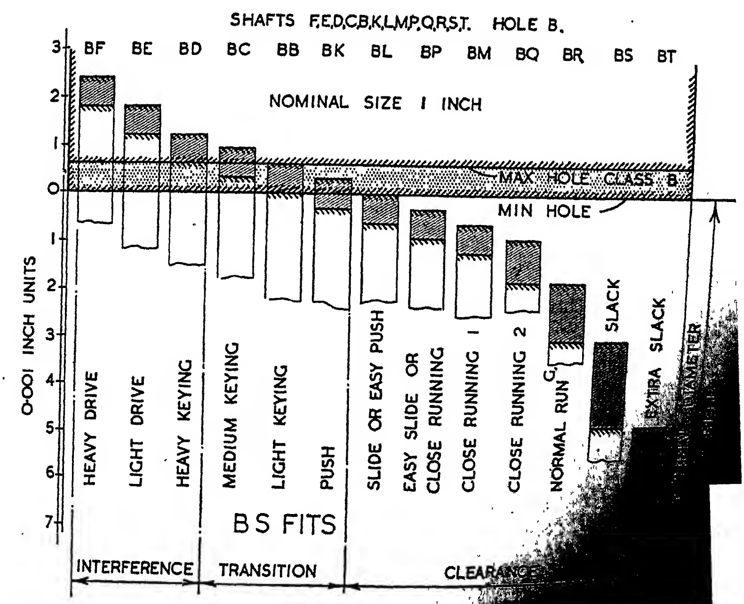


FIG. 333.

In the International Standards Association (I.S.A.) system sixteen grades of workmanship are catered for and the variation in the tolerance, on a 25-mm. nominal size, is shown in Fig. 334. The I.S.A. system also

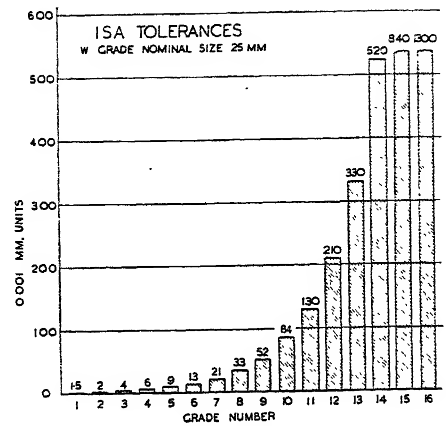


Fig. 334.

lays down a number of tolerance zones for both shafts and holes and the positions of these zones relative to the reference line are indicated by small (lower case) letters for shafts and capital letters for holes. Some indication of these zones is given in Fig. 335, again for a nominal size

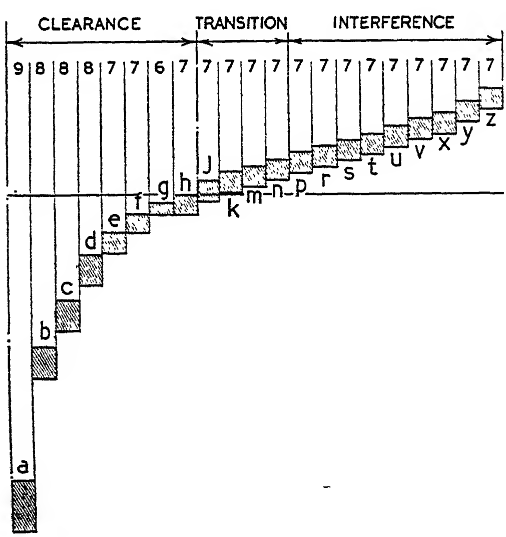


Fig. 335.

of 25 mm.; but for a full consideration of the system the reader is referred to the reports of the Association.

Wear Allowances in Limit Gauges. Since the *Go* gauge must pass over every piece of work that is gauged it will be subject to wear; a female gauge will get bigger while a male gauge will get smaller. In either case it would begin to pass work which was beyond the specified limit, and since the whole object of using a limit gauge is to make certain that the work lies between the specified limits it follows that some allowance must be made for the wear that will occur. Because the *Not Go* gauge will actually pass over only faulty work that will be rejected and which, it is hoped, will be a very small proportion of the whole, it is not necessary to make any allowance for wear on the *Not Go* gauge. Let the limits between which the work must lie be x and y and let the amount to be allowed for wear of the *Go* gauge be w, then it follows that the nominal dimensions for the ends of the gauge would be $x-w$ and y. Hence, when the gauge is new, the tolerance is $(x-w)-y$ and is reduced by the amount allowed for wear. Thus it is desirable to reduce the gauge wear to a minimum and the wearing faces are frequently chromium plated, or may sometimes be faced with tungsten carbide, for that purpose.

Gauge Tolerances. In the same way as the cost of a piece of work is reduced by permitting some variations from the nominal size so the cost of a gauge can be reduced by permitting the gauge-maker some tolerance. Obviously the gauge-maker's tolerance must be much less than, and is commonly made $\frac{1}{10}$ of, the gross tolerance. Let the amount of the gauge-maker's tolerance be g and suppose it is required that every new *Go* gauge shall have its full wear allowance w, then it follows that the *Go* gauge may lie anywhere between the limits $x-w$ and $x-w-g$ as shown in Fig. 336. Similarly, the *Not Go* gauge may lie anywhere between the limits y and $y+g$. Thus the net tolerance remaining to the workman, supposing the *Go* gauge to be made to its lower limit and the *Not Go* gauge to its upper limit, is $(x-w-g)-(y+g)=x-y-w-2g$ and the effect of permitting the gauge-maker a tolerance g has been to reduce the workman's tolerance by $2g$. Now the saving in the cost of making the gauge consequent on permitting a tolerance on it is only realised once, whereas the extra cost on the work consequent on the reduction of the workman's tolerance will be felt on every piece of work, hence it may be false economy to reduce the gauge cost by permitting a gauge tolerance.

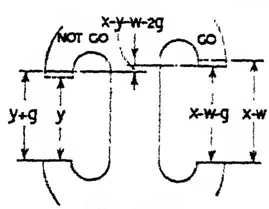


Fig. 336.

Inspector's Gauges. Work that has been made by a workman using his limit gauge is subsequently checked by a shop inspector using a

similar gauge, and because of variations in the actual sizes of the gauges due to the gauge-maker working to the high limit in one case and the low limit in the other it is possible for work that has been passed by the workman's gauge to be rejected by the inspector's gauge. For example, considering the *Go* ends, suppose the inspector's gauge is made to the low limit, $x-w-g$, in Fig. 336, while the workman's gauge is made to the upper limit, $x-w$, then a piece of work lying between those limits would be passed by the workman's gauge but would be rejected by the inspector's gauge as being too big. Generally when this happens all that is done is to interchange the gauges but this may not always be practicable. A similar difficulty may arise when a piece of work is made by one firm for another if the manufacturing firm's gauges are made to the same nominal size as those of the purchaser's and to avoid such occurrences the British Standards Institution has ruled that the gauges used for inspection by a purchaser must pass all work that lies within the prescribed limits. Considering first the *Not Go* gauges, this means that the upper limit for the purchasing firm's gauge is y and, if a gauge tolerance is permitted, the lower limit might become $y-g$. Also the lower limit for the *Go* gauge must be x and hence, assuming a gauge tolerance is permitted, the upper limit may become $x+g$. Hence, even when the purchaser's gauges are quite new, they *may* pass work that lies anywhere between the limits $x+g$ and $y-g$. This is a point that must be borne in mind by the purchaser.

Check Gauges. These are gauges that are sometimes used in gauge rooms to enable shop gauges to be checked rapidly at frequent intervals. There will be a double-ended check gauge for each end of each shop gauge. Referring to Fig. 336, the check gauge for the *Not Go* end of the gauge there shown would be a double-ended male gauge the nominal dimensions of the ends being respectively y and $y+g$, the first being the *Go* end and the second the *Not Go* end. With the great improvement in measuring instruments that has been made during the last twenty years the practice of checking gauges by direct measurement has increased and the use of check gauges has declined.

Other Forms of Gauge. Space is not available to describe all the great variety of gauges used in workshops; only a few of the more important types can be dealt with. Adjustable gauges, which can be set to any desired limits within their capacity, are now widely used, but the evolution of a satisfactory adjustable gauge was by no means a simple matter and many early attempts were failures. One of the earliest successful adjustable gauges was the *Wickman*, an example of which is shown in Fig. 337. After adjustment the setting mechanism is concealed by applying a lead seal so that the setting cannot be altered by unauthorised persons. The use of an adjustable gauge eliminates any need for a gauge tolerance and reduces the amount that must be allowed for wear

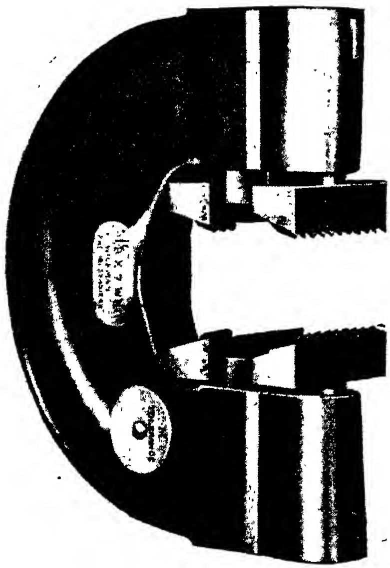


FIG. 337.

to a negligible amount, thereby making the whole of the gross tolerance available to the workman.

A gauge for checking a taper hole is shown in Fig. 338; lines A and B define the limits for the hole. Such a gauge does not provide any real check on the angle of the taper unless it is coated with some marking substance such as red lead "raddle" or prussian blue and then twisted in the hole, the resulting marking being observed. A male taper may be checked by a stepped ring gauge as indicated in Fig. 339, the limits being determined by the depth a of the step.

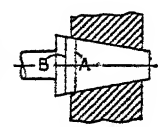


FIG. 338.

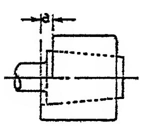


FIG. 339.

A simple gauge for checking the centre distance of two holes is shown in Fig. 340. The centre distance C is made equal to the nominal centre distance of the work and the pins are made smaller than the low limits for the holes. Let d_1 and D_1 be the diameters of the pins and d_2 and D_2 the diameters of the largest holes. Then the maximum variation in the centre distance of the work, i.e. the tolerance, will be

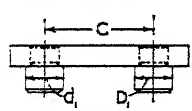


FIG. 340.

$$\left[C-\frac{d_1+D_1}{2}+\frac{d_2+D_2}{2}\right]-\left[C+\frac{d_1+D_1}{2}-\frac{d_2+D_2}{2}\right]=(d_2+D_2)-(d_1+D_1)$$

but if the holes happen to be both to the low limit, the tolerance on the centre distance would be reduced to $(d_3+D_3)-(d_1+D_1)$ where d_3 and D_3 are the diameters of the smallest holes; in this case the tolerance is reduced by the sum of the tolerances on the holes. Alternatively the centre distance of the gauge pins can be made $C+T/2$, where T is the tolerance on the centre distance, and the pins be made equal to $d_2-T/2$ and $D_2-T/2$ respectively. This *Go* gauge will definitely reject all work in which the centre distance is outside the prescribed limits but it may also reject a certain amount of correct work. To check the centre distance independently of the variations in the diameters of the holes a more complicated gauge having tapered pins, one of which is free to slide, must be used.

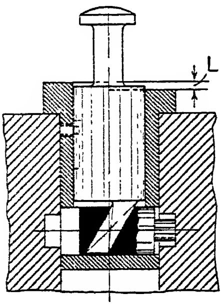


FIG. 341.

Fig. 341 shows a gauge for checking the depth of a recess; the limits are determined by the depth of the step L.

The Measurement of Angles. There are several methods of measuring angles and the method used in any particular case will depend on circumstances. One method is by means of *angle gauges* or *angle templates* as shown in Fig. 342. These are pieces of gauge steel which have been accurately formed to the angle engraved on them; they are used by fitting them in turn on to the piece to be gauged until one is found that fits perfectly, the fitting being judged by holding work and gauge in front of a light and observing if any light is visible between gauge and work. Since a gap of 0·0001 in. is easily seen, this method is limited as regards accuracy chiefly by the accuracy of the gauges themselves and the extent of the range of angles represented. Instead of a large number of fixed gauges a single adjustable gauge, as shown in Fig. 311 (bottom left), may be used. In this, which is commonly called a *bevel protractor*, the angle between the blade and stock is read off a graduated scale against an index. In a refined form of this gauge the scale is engraved on glass and is observed through a magnifying eyepiece. While the adjustable gauges are much more convenient to use than the fixed gauges they are not so accurate, being subject to errors (*a*) in the graduated scales, (*b*) in the reading of the scale, and (*c*) due to eccentricity of scale and pivot. The scales and verniers of these instruments generally permit of settings being made to within about 5 minutes of arc. A second method of measuring an angle is indicated in Fig. 343. The method may conveniently be called "measurement by first principles." Two measurements L_1 and L_2 are

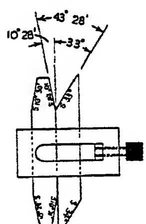


FIG. 342.

made as indicated and, knowing the height h of the blocks BB and the radii r of the rollers RR the angle 2θ is easily calculated, being given by the equation $\tan\theta=\frac{L_2-L_1}{2h}$. A similar method may be used for large taper rings; for small rings the method indicated in Fig. 344 is convenient. Clearly $\sin\theta=\frac{r_2-r_1}{O_1O_2}=\frac{r_2-r_1}{r_1-r_2+h_2-h_1}$. These methods are obviously more useful in a laboratory than in a gauge room.

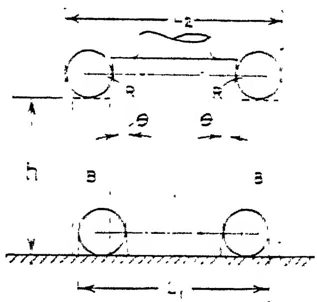


FIG. 343.

A third method is by means of a clinometer. This consists essentially of a sensitive bubble tube carried by an arm which is pivoted to the frame of the instrument. The arm can be set at any required angle to the base of the instrument by means of a worm which engages a toothed arc attached to the arm. The worm spindle is carried in the frame. The angle may be read off from a scale attached to the arm in conjunction with a graduated micrometer thimble carried by the worm spindle. Clinometers are made in various sensitivities, this being determined chiefly by the sensitivity of the bubble tube. The precision clinometer made by the Société Genevoise is graduated to 10 seconds of arc. Clinometers are much used to enable the surface of a piece of work to be set at a required angle to either a marking-out table or a machine work table as follows. The clinometer is placed on the table and is adjusted until the bubble is central; the scale reading is then observed. The clinometer is then adjusted until it gives the same reading plus the required angle and, finally, it is placed on the surface of the work, which is being set, and the work is adjusted on the table until the bubble is again central.

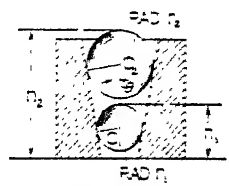


FIG. 344.

Clinometers in which the inclination of the bubble tube is read directly off a glass scale by means of a microscope eyepiece are now available, an example being shown in Fig. 345.

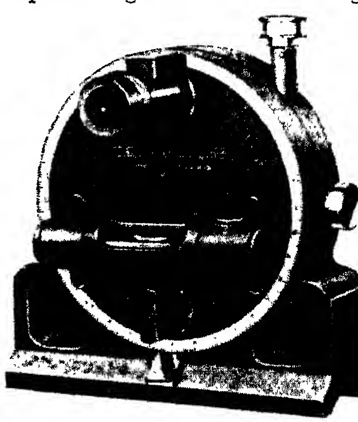


FIG. 345.

A fourth method of setting out, or measuring, angles is by means of a *sine-bar*. Sine-bars are made in various forms and one very convenient

form is shown in Fig. 346. The surfaces YY are finished accurately in line with each other and accurately parallel to the surface XX. The dimension L is also accurately determined. The bar is supported on a

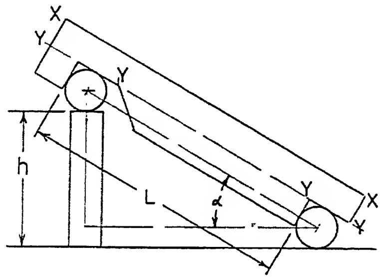


FIG. 346.

surface plate or table, on a roller at one end and on an equal roller standing on a block gauge, height h, at the other end. Then clearly the angle between the surface XX and that of the table is given by $\sin\alpha=\frac{h}{L}$. The sine-bar may be regarded as a specialised form of measurement from first principles; a somewhat less specialised form is indicated in Fig. 347,

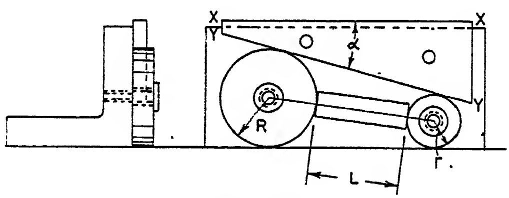


FIG. 347.

where it enables a piece of work to be set so that its surface XX can be ground accurately at some angle α with the previously ground face YY. Discs radii R and r are used in conjunction with an end gauge of length L; the angle α is clearly given by $\sin\frac{\alpha}{2}=\frac{R-r}{R+r+L}$. The set-up is facilitated by securing the discs and work to an angle-plate as indicated.

A fifth method of measuring angles is by means of a dividing head as has been described in Chapter 15.

The Checking of Form Gauges and Tools. Form gauges usually consist of pieces of gauge plate which have been finished so as to be the exact mate of the work they are to check. They can sometimes be checked by measurement by first principles, but the most convenient method is undoubtedly by means of a *contour projector*. This is an instrument which throws an enlarged shadow of a piece of work, placed

in it, on to a screen ; by comparing the enlarged shadow with an enlarged drawing or template of the work the latter is quickly checked. These instruments are made by numerous makers and give magnifications up to 50 times. The optical system must obviously not introduce any appreciable distortion if the method is to be of any use and, while the difficulties have now been mostly overcome, the liability to distortion and lack of definition still limit the size of the work it is practicable to project and the degree of magnification. In these instruments the work is usually supported on a carriage which may be traversed in two directions, at right angles, by means of micrometer screws ; by traversing the work until parts of the enlarged shadow coincide with an index line on the screen, measurements may be made by means of the micrometers ; alternatively the enlarged shadow may be measured directly.

The Measurement and Gauging of Screw Threads. The contour projector was originally developed for the examination of screw threads and is still used principally for that purpose ; the gauging of screws is, however, a complex matter and it is necessary to consider first the elements or dimensions which determine the size of a screw ; an ordinary Whitworth form thread will be dealt with as being the commonest type. Fig. 348 shows such a thread and indicates its elements ; these are :

1. *Major, nominal,* or *outside* diameter D.
2. *Minor* or *core* diameter *d*.
3. *Effective* diameter *e*.
4. *Pitch* p.
5. *Angle* a.
6. *Crest radius* r_c.
7. *Root radius* r_r.

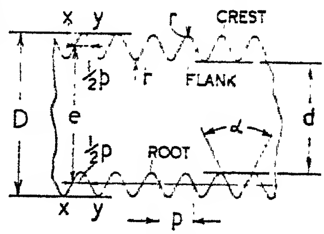


FIG. 348.

The elements are mostly obvious but the effective diameter and the pitch need definition. The effective diameter is defined as the diameter of the imaginary cylinder which intersects the surface of the thread in such a manner that the intercept (*xy*, Fig. 348) on a generator of the cylinder, between the points where it meets the opposite flanks of the thread groove, is equal to half the nominal pitch of the thread. The pitch is the distance, measured parallel to the axis of the screw, between corresponding points on adjacent thread forms in the same axial plane.

The effective diameter is important because it determines the strength of the screw.

It is quite easy to verify that a male screw is not too big in any element by employing a *full-form Go* gauge. This gauge takes the form of a nut, that is, it is a complete ring threaded with a full thread internally and its axial length must be equal to that of the screw being gauged or, at least, equal to that of any female screw that will be mated with the screw being gauged. Similarly, it is easy to verify that a female screw is not too small

in any element by using a full-form *Go* gauge which will take the form of a plug threaded with a full thread.

It is not so easy to verify that a male screw is not too small in any element. *A full-form Not Go gauge will not ensure this.* For obviously if, say, the major diameter was correct and the minor diameter was too small the full-form *Not Go* gauge would still not go and would not cause the screw to be rejected. Again, if all the elements except the pitch were correct and the pitch was too small, the full-form *Not Go* gauge would not go and the work would not be rejected as it ought to be.

It is necessary, in fact, to employ a number of *Not Go* gauges each one of which checks only one element of the screw.

This is not a peculiarity of screws but is a general principle applicable to the gauging of all kinds of work and this principle had better be dealt with now.

Not Go Gauges should not be Full-Form Gauges. This can easily be demonstrated by considering the gauging of a simple circular disc. A full-form *Go* gauge, consisting of a plate with a circular hole cut in it, will clearly reject any disc that is too large in any diameter, but a full-form *Not Go* gauge, consisting of a similar plate with a slightly smaller circular hole in it, would not reject an elliptical piece of work, no matter how much too small the minor diameter was, provided the major diameter was not too small, as is indicated in Fig. 349. If, however, the *Not Go* gauge was a snap gauge (as shown in Fig. 329) and was tried on the work in several positions, the elliptical disc would be rejected if its minor axis was too small. The snap gauge gauges only one dimension (a single diameter) at a time and all *Not Go* gauges should, theoretically, do likewise.

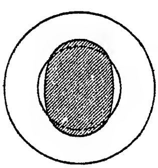


Fig. 349.

A similar consideration will show that a *Go* gauge *should* be a full-form gauge and that a snap *Go* gauge, theoretically, will *not* ensure that all work that is too big will be rejected. In practice the use of snap-type *Go* gauges does not lead to any difficulties, at least for work finished on lathes or cylindrical grinding machines, because those machines do not tend to produce work which is appreciably out of round. The principle that *Go* gauges should be *full-form* gauges while *Not Go* gauges should check only one dimension is sometimes known as *Taylor's* principle.

The Gauging of Screws in Practice. In practice male screw threads are commonly gauged by means of a full-form *Go* gauge and three single-element *Not Go* gauges; the full-form *Go* gauge is often discarded in favour of a snap gauge with a full thread form; this is satisfactory because, as mentioned above, out of roundness is not usually appreciable. The *Not Go* gauges check the major, minor, and effective diameters, the

latter in combination with the pitch, since it can be shown that, for the small variations under consideration, an error in effective diameter can be compensated by a corresponding error in pitch and vice versa. The gauges take the form of snap gauges with special anvils as indicated in Figs. 337 and 350.

The crest and root radii and the thread angle are maintained correct by indirect methods, chiefly by examining the tools used to cut the threads, i.e. chasers, etc., in a contour projector.

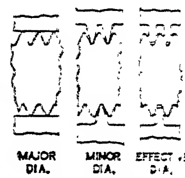


FIG. 350.

Female screws are sometimes gauged by a full-form *Go* gauge and three *Not Go* gauges which are the male counterpart of the gauges shown in Fig. 350, but the majority of female screws are not gauged at all; instead the taps that produce them are carefully verified.

In gauge rooms male screws are frequently measured by the *three-wire* method indicated in Fig. 351. Three small cylindrical rods or wires are placed in the thread V's as shown so as to enable the effective diameter to be measured by means of an ordinary micrometer. Tables are available giving the effective diameters in terms of the micrometer readings, wire diameter and thread pitch. Micrometers with anvils similar to those indicated in Fig. 350 are also obtainable. Thread angles may be measured by means of a microscope fitted with an eyepiece having a rotatable fiducial line and graduated scale, the line being made to coincide first with one flank and then with the opposite flank. If the screw is supported on a carriage which can be traversed underneath the microscope parallel to the axis of the screw, by means of a micrometer, the pitch may be measured by aligning the fiducial line first with one flank and then with the next consecutive flank.

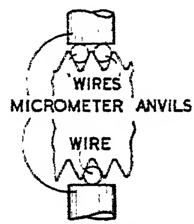


FIG. 351.

The Gauging of Toothed Gears. The gauging and measurement of toothed gears is a complex matter and can only be dealt with very briefly in this book. The errors that may be present in a straight-toothed spur gear can be grouped, roughly, into three groups, namely: (1) Spacing errors; (2) Errors of concentricity; (3) Errors in tooth outline; but it is not generally very easy to measure the errors of one group independently of those of the other groups. Spacing errors, for example, in the absence of the other kinds of error, would be shown up by measuring the chordal pitches all round the gear; this can be done by means of gauges of the type shown in Fig. 355. Similarly, concentricity errors, in the absence of the other types, can be detected by mounting the gear between centres, placing a cylindrical plug in each tooth space in turn, and taking a dial indicator reading on the plug as the gear is revolved; the set-up is

indicated in Fig. 352; the plug can be held in place conveniently by means of a rubber band.

Errors of tooth outline, for involute teeth, can be detected in several ways but they mostly are based on the following property of involutes of circles. If the base circle A of an involute BB (Fig. 353) is rolled without slip along a straight line CC then the point D in which the involute intersects CC will be a fixed point. Consequently a lever E pivoted on a fixed point and arranged with its tracing point coincident with D will not be moved and the reading of an indicator F will remain constant. Any variation of the indicator reading shows up some inaccuracy in the involute profile. The machines that use this principle range from the simplest possible set-up to quite complicated arrangements which produce a permanent record of the errors in the form of a graph.

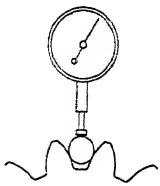


Fig. 352.

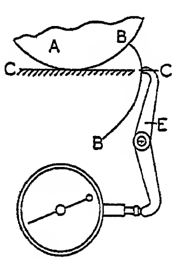


Fig. 353.

Errors of concentricity and spacing both produce errors in the normal pitch of gear teeth and so gauges for checking the normal pitch are widely used. The Maag instrument for this purpose is shown in Fig. 354.

When teeth are being cut the depth to which the cutters must be sunk is determined either by means of simple plate gauges or by measuring the chordal thickness of the teeth. This is conveniently done by means of special vernier callipers, an example of which is shown in Fig. 355. The auxiliary slide, perpendicular to the main slide, enables the main slide measurement to be taken at any desired depth; tables are given in

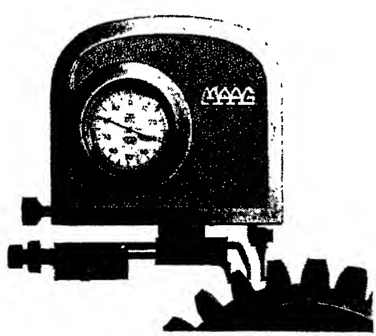


Fig. 354.

many engineering handbooks from which the perpendicular distance from the centre of the chord subtended by the tooth to the outside circumference of the gear, i.e. the required setting for the auxiliary slide, can be

looked up. A correction will have to be applied if the outside diameter of the gear differs from the standard dimension.

After cutting a gear it is frequently checked by meshing it with a specially accurate master gear in a fixture which permits a variation in the centre distance between the shafts carrying the gears. A spring presses the gears together and a dial indicator shows up any variation in

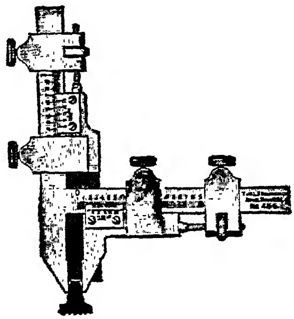


Fig. 355.

the centre distance as the gears are rotated. In the more elaborate fixtures the variation is recorded on a chart. One such fixture, made by Messrs. Parkinson & Son, Ltd., of Shipley, is shown in Fig. 356.

Projection machines, such as are used for checking screw threads, are sometimes used to check gear teeth, while at the National Physical Laboratory gear teeth are checked on a special machine which reproduces

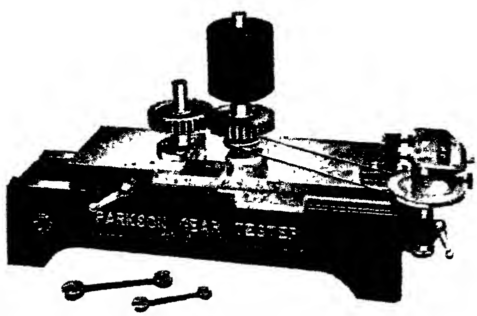


Fig. 356.

the outline of each tooth as a fine line drawn on smoked glass; this trace is then enlarged by projection on to a screen. For a description of this machine the reader is referred to *Engineering*, July 27, 1923.

Special machines are made for checking the accuracy of hobs and Fig. 357 shows the principle of one made by the Michigan Company. The hob being tested is carried on an arbor between centres and the

arbor is connected to an accurately cut pinion meshing with a rack, as shown, so that when the hob rotates the rack moves in synchronism. The rack slide carries an adjustable " sine bar " which imparts motion to the indicator slide. The sine bar being set at the appropriate angle for the lead of the hob teeth it follows that when the hob is turned through

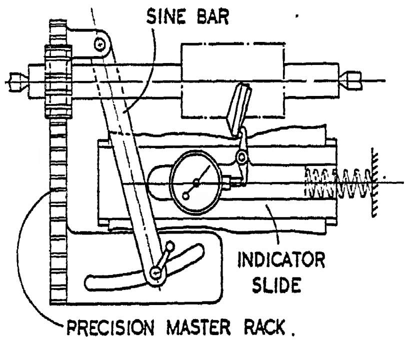


FIG. 357.

an angle equal to one tooth space the indicator reading should be the same as at the start and any difference in its reading shows up an error in the hob teeth. The sine bar is the equivalent of an accurate lead screw, but it should be obvious that the spur pinion and rack connecting the motion of the sine bar and hob mandrel must be made to a high degree of accuracy if accurate results are to be obtained.

Gauging Machines. In gauging, as in actual production, efforts are continually being made to reduce costs and in pursuance of this object machines have been developed to gauge pieces of work automatically. Probably the first of such machines were those used nearly forty years ago for gauging cartridge cases; these were purely mechanical and performed some dozen gauging operations on each case. Within the last year or so the Ford Company has developed a machine for the automatic gauging of motor engine crankshafts; for a description of this machine the reader is referred to *Machinery*, July 25, 1940. Obviously the initial costs of such a machine can be justified only when very large quantities of work are being produced.

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